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Soil Response to Cropping Sequences and Grazing Under Integrated Crop-livestock System

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SOIL RESPONSE TO CROPPING SEQUENCES AND GRAZING UNDER INTEGRATED CROP-LIVESTOCK SYSTEM

BY

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SOIL RESPONSE TO CROPPING SEQUENCES AND GRAZING UNDER INTEGRATED CROP-LIVESTOCK SYSTEM

This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABBREVIATIONS

ACE	Acid Extracts
ANOVA	Analysis of Variance
BD	Bulk Density
$CaCl_2$	Calcium Chloride
$C_3Cl_2N_3NaO_3$	Sodium Dichloroisocyanurate
CFDE	Chloroform Fumigation Direct Extraction Method
$C_7H_5NaO_3$	Sodium Salicylate
CS	Conventional System
CWE	Cold-water Extracts
DAS	Dry Soil Aggregate Stability
DF	Dilution Factor
DW	Dry Weight
EC	Electrical Conductivity
HCl	Hydrogen Chloride
HWC	Hot-water Extractable Carbon
HWE	Hot-water Extracts
ICLS	Integrated Crop-livestock System
KCl	Potassium Chloride
K_2SO_4	Potassium Sulfate
MBC	Microbial Biomass Carbon
MBN	Microbial Biomass Nitrogen
MUB	Modified Universal Buffer
NaOH	Sodium Hydroxide
NH_4Cl	Ammonium Chloride
PNG	p-nitrophenyl-β-D-glucoside
RCBD	Randomized Complete Block Design
SOC	Soil Organic Carbon

SWR	Soil Water Retention
TC	Total Carbon
THAM	Tris (hydroxyethyl) Aminomethane
TN	Total Nitrogen
WAS	Wet Soil Aggregate Stability

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ABSTRACT

SOIL RESPONSE TO CROPPING SEQUENCES AND GRAZING UNDER INTEGRATED CROP-LIVESTOCK SYSTEM

HANXIAO FENG

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Integrated crop-livestock system (ICLS) is helpful in diversifying a farm for improving its long-term sustainability and economic benefits. In the United States, the ICLS has been increasing in recent years because of its economic and environmental benefits. However, the impacts of ICLS on soil quality is not well documented in North Dakota. The objective of our study is to assess the impacts of cropping sequences and cattle grazing on the selected soil properties in the crop diversity and livestock integration practice. This study site was established in 2010 at the Dickinson Research Extension Center, Dickinson, North Dakota. The study design was a randomized complete block design with 3 replications. Treatments were included the five 5-yr cropping sequences and one continuous 5-yr spring wheat (control, CNT). The five crop rotation crops were sunflower (*Helianthus annuus* L.)-spring wheat (*Triticum aestivum* L.)-multi-species cover crop-corn (*Zea mays* L.)-field pea (*Pisum sativum* L.) and barley (*Hordeum vulgare* L.) (S1), spring wheat-cover crop-corn-pea/barley-sunflower (S2), cover crop-corn-pea/barley-sunflower-spring wheat (S3), corn-pea/barley-sunflower-spring wheat-cover crop (S4), and pea/barley-sunflower-spring wheat-cover crop-corn (S5). The cover crop included winter triticale (*Triticosecale* Wittm.) and hairy vetch planted in September for spring hay production the following June. A mixture of seven species cover crops was planted for fall and winter cow grazing. Grazing treatment included grazed and un-

grazed. Soil samples were collected from 0-5, 5-15, 15-30, 30-45, and 45-60 cm in June 2016 and April 2017. Soil bulk density (BD), soil organic carbon (SOC), total nitrogen (TN), soil wet aggregate stability (WAS), soil water retention (SWR), carbon and nitrogen fractions (labile, stable, and inert), microbial biomass carbon, urease and beta-glucoside enzyme activity were measured in this study. The results showed that the cropping sequences under ICLS numerically increased SOC, urease, beta-glucoside enzyme activity and decreased the BD values at 0-5 cm depth, however, differences were not significant. Grazing only impacted the soil BD at shallow depth (0-5 cm). It can be concluded that soil compaction created by livestock can be alleviated by crop rotation, and ICLS is a good practice to be conducted in North Dakota which brings beneficial environmental impacts and economic return. Future study is needed to characterize the long-term grazing and cropping sequences impact on soil quality.

CHAPTER 1

INTRODUCTION

Crop diversification can be considered as the application of adding various crops into agricultural system on a particular farm with taken different economic return from added crops into consideration to minimize market price risk, increase climate change adaption as well as the complementary marketing opportunities (Clements et al., 2011). Crop diversification such as integrated crop-livestock system (ICLS), diverse crop rotations, and less disturbed field systems can enhance soil quality. Some of these benefits of soil quality due to diverse crop rotations include increased soil water storage, availability of favorable environment for the soil microbial decomposition of complexed organic matter into plant available ingredients or nutrients (Karlen et al., 2006). Crop rotations when combined with cover crops provide assistance in boosting the agronomic productivity and economic outcomes (Smith et al., 2008). Further, crop rotations enhance soil carbon and nitrogen concentration, microbial biomass carbon and nitrogen pool (Chateil et al., 2013; McDaniel et al., 2014; Tiemann et al., 2015), and mitigate the pest pressure by breaking down the pest cycle (O'Rourke et al., 2014). In this study, ICLS and diverse crop rotations are the main focus areas, hence discussed in detail hereafter.

The ICLS brings positive interactions between crops and livestock together with social and economic benefits (Allen et al., 2007; Maughan et al., 2009). The ICLS is a good management to achieve the balance between agricultural production and environmental quality (Lemaire et al., 2014). In the United States, the application of ICLSs has been increasing in recent years because of its various economic and environmental benefits (Thornton, 2010b). The application of appropriate ICLSs can

enhance soil organic carbon (Rufino et al., 2006) and carbon sequestration, minimize the emissions of soil surface greenhouse gases (Soussana and Lemaire, 2014) and N loss (Korsaeth and Eltun, 2000), increase the crop yield, and enhance the higher economic return (Baudron et al., 2014; Tracy and Zhang, 2008) as compared with the continuous simple cultivated farming systems. These integrated systems are beneficial in improving the soil quality, however, application of these systems depend upon the local environmental conditions.

Grazing when used appropriately can help in improving the soil quality, societal and economic benefits (Follett and Reed, 2010; Savadogo et al., 2007). It was reported that optimum grazing rate under no-till system positively impacts weed pressure and economic benefits due to less extra feed need during the winter period (Teague et al., 2011). Grazing can increase soil fertility because of the animal excrement and urine input on the soil surface, therefore, more available nutrients can be supplied to crops for their growth and production (Russelle et al., 2007). The synergistic effect may be found between crops and livestock under the ICLS as the livestock supply nitrogen and other nutrients for crop growth and in-return, crop residue or cover crop supply as feed to the livestock. However, grazing impacts on soil properties are not consistent across the various environmental settings due to the complexed factors interaction and other factors, such as climate, grazing time, grazing intensity, soil moisture content, soil structure and soil condition (Savadogo et al., 2007). The study conducted in South Tunisia illustrated that removal of the grazing livestock from arid degraded steppes are helpful in protecting the soil quality (Jeddi and Chaieb, 2010). However, overgrazing, continuous grazing or higher intensity grazing rate can intensified soil wind erosion, reduce soil organic carbon

and nitrogen content and increase the loss of nutrients on the surface soil depths (Neff et al., 2005) and reduce the soil biochemical properties (i.e. soil enzyme activities), and consequently led to soil deterioration (Yong-Zhong et al., 2005).

Cover crops in the United States can be defined as plants based provisional or seasonal soil cover which have the potential benefits for soil conservation, soil quality enhancement, soil fertility, soil structure, weed control, and nutrient cycling (Sulc and Franzluebbers, 2014). These cover crops in cropping systems have shown numerous benefits including higher water infiltration, soil organic carbon accumulation, soil ecology stability, minimize the loss of water, nutrients and soil erosion, lower the weed and disease pressure, fix and provide nitrogen for crops growth (especially for the leguminous plants) (Franzluebbers, 2007). Cover crops also serve as a nutrient sink which lower the water and nutrients leaching, thereby, maintaining or improving the soil fertility. Cover crops with deep roots can grow through compacted soil and diminish the soil compaction of shallow depth, increase the soil aeration and water infiltration. These cover crops are helpful in reducing the wind and water erosion by protecting the soil surface with the surface residues and the living stubble or vegetation (Creamer et al., 1996; Langdale et al., 1991; Silva and Moore, 2017). The residues on the soil surface can enhance activities of microbes and hence help in the soil organic matter decomposition (Costa et al., 2015a). In addition, winter cover crops can be supplied as forage for livestock, which can decrease winter feed costs (Lawrence and Strohbehn, 1999; Sulc and Franzluebbers, 2014).

Integrated livestock into cropping system, if not managed properly has the potential to increase the soil bulk density, soil penetration resistance due to the hoof

traffic, and cause soil compaction and breakdown the soil aggregates (Tracy and Zhang, 2008). Therefore, an improved understanding of soil physical, chemical, and biological properties as impacted by crop diversification and grazing treatment under ICLS is important to study under local conditions. Thus, the present study was conducted in Dickinson, North Dakota to assess the impacts of grazing and diverse cropping sequences on selected soil properties.

Objectives

The objective of this research was to investigate the impacts of cropping sequences and livestock grazing under an ICLS on the selected soil properties in the crop diversity and livestock integration practice in North Dakota, USA. The specific objectives are as follows:

Objective 1: To access the effects of cropping sequences and cattle grazing on soil physical, hydrological, and chemical properties (soil pH, electrical conductivity, bulk density, wet soil aggregate stability, water retention, soil organic carbon and total nitrogen) under ICLS in North Dakota, USA.

Objective 2: To evaluate the response of soil biological and biochemical properties (urease, beta-glucosidase enzymes activities, soil microbial biomass carbon, microbial biomass nitrogen, carbon fractions and nitrogen fractions) to crop diversity and cattle grazing practice under ICLS in North Dakota, USA.

CHAPTER 2

LITERATURE REVIEW

2.1. Integrated Crop-Livestock System (ICLS)

Integrated crop-livestock system (ICLS) is a method of diversifying a farm or a ranch for improving its long-term sustainability and profitability, and generate synergistic effect in systems accompany with environmental and economic benefits (Allen et al., 2007; Maughan et al., 2009). The ICLS involves rotations of crops and cover crops with the livestock grazing of cover crops, grazing of crop residue after harvest, or grazing annual crops for winter feed instead of mechanical harvesting (Russelle et al., 2007; Şentürklü et al., 2017). The ICLS has been adopted across the world including Australia (Bell et al., 2014), Kenya (Tittonell et al., 2009), Brazil (Salton et al., 2014), China (Hou et al., 2008), west Africa (Fernandez-Rivera et al., 2002), America (Lemaire et al., 2014; Senturklu et al., 2017), India (Erenstein and Thorpe, 2010; Rao and Hall, 2003), and various other countries. In the United States, the ICLS has been increasing in recent years because of their economic and environmental benefits as people getting more concern about the natural resource degradation and sustainable profitability (Russelle et al., 2007; Thornton, 2010a).

Obtaining high crop yield and receiving considerable economic benefits from year around are the ideal goal for all the farmers (Flores et al., 2008). To achieve these goals, an improved soil quality can play a significant role. Soil quality in the ICLS depends on the soil and pasture management (Costa et al., 2009). It can be enhanced by using crop diversification such as the ICLS. It is considered that ICLS is more environmentally and economically supported management practices compared to the monoculture systems

(Russelle et al., 2007). Many advantages of ICLS have been reported in the recent years. Some of those benefits include: improvement in soil fertility with an on-farm input and livestock manure, reduction in the application of manufactured chemical fertilizer, and maintaining or improving the soil quality. The integrated systems can increase crop yield and economic benefits stability by increasing the cycling nutrients and enhancing crops diversity through various crop rotations (Franzluebbers, 2007; George et al., 2013; Hilimire, 2011). These systems are favorable for soil parameters that are beneficial for improving the soil quality (Acosta-Martínez et al., 2004a). The ICLS can increase soil organic carbon, protect and reinstate degraded soil and alleviate greenhouse gases emissions (Lemaire et al., 2014), improve crop production (Bell et al., 2014; Maughan et al., 2009; Tracy and Zhang, 2008), nutrient cycling (Franzluebbers and Stuedemann, 2014), total nitrogen, soil microbial biomass carbon, and water aggregate stability, and reduce soil penetration resistance (George et al., 2013), and N losses (Tracy and Zhang, 2008). Furthermore, ICLS controls weeds and reduces feed resource pressure especially during the winter time (Devendra and Thomas, 2002). Cover crops especially the legumes incorporated in the ICLS improve nutrient cycling and hence reduce the application of commercial fertilizer (Sanginga et al., 2003; Sentürklü et al., 2016). The ICLS is suggested as a cost-efficient practice which can maximize utilization of the cropland to achieve higher agricultural productivity and minimize the negative impact on soil quality by utilizing the synergistic effect of complexed components inside the systems (Martins et al., 2016). For instance, cover crops and crop residue supply feed for livestock and conversely crops capture nutrients from the livestock excreta (Sentürklü et al., 2016). Numerous environmental benefits from ICLS could be achieved when

perennial and legume forages are included in the crop rotations such as enhancement of the soil porosity, soil fertility and carbon sequestration (Russelle et al., 2007). However, there are also some negative concerns about the ICLS and some of them include such as livestock traffic creates soil compaction and destroys soil aggregates if these systems are not managed properly, and high initial cost related to fencing. Several soil parameters response to ICLS will be discussed in the following paragraphs of this chapter.

2.2. Crop Diversity Impacts on Soils under ICLS

Crop rotation is a biological diversity practice of growing a series of dissimilar or different types of crops in the same area in sequenced seasons. It can improve soil quality, nutrient cycling, water storage, crop yield, and pest management, and minimize soil erosion (Francis and Clegg, 1990). Some studies have documented that using the different crops in the rotation can enhance biomass and soil organic carbon (Havlin et al., 1990), cropping system productivity and environmental benefits. Cover crop in rotation is one of the most efficient ways to supply feed to the livestock. It was documented that in the ICLS, cover crop and crop residue after harvesting remain on the soil surface can help in reducing the soil compaction. Diverse crop rotations with forages included in ICLS has various advantages in building environmental health and enrich economic return (Russelle et al., 2007; Sentürklü et al., 2016). Crop rotation systems involving different types of root systems are favorable in nutrient cycling and soil organic matter decomposition (Costa et al., 2015b).

2.3 Impacts of Grazing on Soils under ICLS

Integrating livestock into cropping system has been used since last century or even earlier than the modern industrial revolution (Franzluebbers, 2007). Integrating

livestock into cropping systems can raise economic benefits by reducing the external feed source and supply amount of nutrients through animal waste (Liebig et al., 2017). Many benefits were observed by using ryegrass/oats for grazing during the winter such as reducing the weed and pest pressure, and minimizing the soil moisture loss during cropping period (George et al., 2013). Grazing increased the microbial biomass and organic matter accumulation in the soil probably due to the fact that animal grazing promotes crop root growth and soil fertility (Nie et al., 2016). George et al. (2013) documented that light to moderate grazing intensity are beneficial for soil physical and chemical properties by supplying a better environment for soil microbes. However, over-grazing or higher grazing intensity has some negative impacts on soil quality such as increased soil compaction, and reduced soil porosity and hydraulic conductivity (He et al., 2017).

2.4 Response of Soil Qualities to ICLS

The ICLS has strong influence on the changes in soil, chemical, physical, hydrological, and biological properties (Acosta-Martínez et al., 2004a). Some of these properties as influenced under ICLS are mentioned below as:

2.4.1 Soil Organic Carbon

Soil organic carbon is one of the most important chemical index of soil quality, and is a vital element in maintaining and improving soil quality and soil-plant ecosystem (Franzluebbers and Stuedemann, 2008). Crop rotation and grazing play a significant role in impacting soil chemical properties. A long-term study conducted in Planaltina, DF, Brazil on a clayey Oxisol (Typic Acrustox) showed that continuous cropping resulted in an overall decrease of 1.0 to 8.6 Mg ha^{-1} soil organic carbon compared to the control

treatment (Marchão et al., 2009). Similarly, the adverse effect on soil quality was reported by Magdoff and Van Es (2000) that over 9 inches of topsoil of continuous corn was lost as compared with diverse crop rotation in a 60-year study in Missouri. Another study conducted in Mato Grosso do Sul, Brazil on an Oxisol (kaolinitic with clay, silt, and sand contents of 630, 215 and 155 g kg^{-1}, respectively) showed that ICLS practice was a good way to build up soil carbon stock and reduce the greenhouse gases emission compared with a conventional system (CS) consisting of a soybean (*Glycine max* (L.) Merr.) monoculture followed by oats (*Avena strigosa* Schreb. or *Avena sativa* L.) under conventional soil tillage (Salton et al., 2014). Similar conclusion was also reported by Acosta-Martínez et al. (2004a) who showed that soil organic carbon in continuous cotton was reduced by 4.5 g kg^{-1} compared to that in perennial pasture at the 0- to 5- cm depth. Another study carried out in Cerrado demonstrated that ICLS enhanced the soil enrichment and soil carbon sink capacity under no-till system, even with machine traffic effects and large nutrient output (Costa et al., 2015a). A 2-year study conducted by George et al. (2013) in Jackson Co., Florida on an Ultisol, Dothan sandy loam (fine, loamy siliceous, thermic plinthic kandiudults) reported that the influence of grazing on soil organic carbon and organic matter is not due to a simple factor but rely on many factors, such as soil total nitrogen metabolic pathway, soil organic matter decomposition method and rate, because they found that grazing increased the soil organic matter compare to that un-grazed soils at the 0- to 5- and 20- to 25- cm depths in the first year, while opposite trend was detected in the next year that soil organic matter in un-grazed soil was greater than that of grazed soil. They also found that irrigation had effect on soil

organic matter. The organic matter of un-grazed treatment was greater compared to that of grazed soil at the surface depth under non-irrigated condition (George et al., 2013).

2.4.2 Soil Nutrients (Nitrogen)

Soil nitrogen is an important chemical indicator of soil fertility and one of the most crucial nutrient that can influence the soil quality, soil-crop system, and crop productivity. Crop rotation and grazing intensity can impact the soil nutrients cycling pathway. Research located at the North Florida Research and Education Center on an Ultisol, Dothan sandy loam (fine, loamy siliceous, thermic plinthic kandiudults) conducted by George et al. (2013) reported that grazing increased nitrate concentration by three to five times compared to un-grazed soils up to 20 cm depth. However, a long-term experiment located in northeast Lubbock County in the Texas High Plains on a Pullman clay soil (Fine, mixed, thermic Torrertic Paleustolls) under a continuous cotton and integrated crop-livestock systems by Acosta-Martínez et al. (2004a) observed that there was no significant differences in total nitrogen among the continuous cotton treatment and the integrated livestock-crop system with a perennial warm-season grass pasture (*Bothriochloa bladhii*) paddock and two paddocks (two stages) of a rotation (wheat [*Triticum aestivum*]-fallow-rye [*Secale cereale*]-cotton). Similar result was reported by Liebig et al. (2017) from a 12-year experiment located near Mandan, North Dakota, USA on a mix of Temvik-Wilton silt loam soil (Fine-silty, mixed, superactive, frigid Typic and Pachic Haplustolls). They noticed that there were no significant differences in available nitrogen content under grazing and crop rotation treatments. Another study carried out in northern China showed that the content of total nitrogen, available nitrogen, organic matter, available phosphorus and potassium as well as the urease enzyme activity

in the soil decreased with increasing grazing intensity, while the light grazing intensity was the best practice in improving these soil parameters compared to modertate and high grazing intensity (Jiao, Nie et al. 2016).

2.4.3 Carbon Fractions

Carbon fractions include labile carbon, stable carbon, and inert carbon those are extracted with cold water, hot water, and hydrogen chloride (HCl), respectively (Ghani et al., 2003). The hot-water extractable carbon (HWC) is a sensitive parameter to land management practices which is closely linked to soil microbial biomass and soil aggregation, and can be used as a sensitive indicator of soil quality (Ghani et al., 2003). It was found that the HWC concentration negatively impacted by N fertilization application. A long-term study conducted at Indian Head, Saskatchewan by Campbell et al. (1999) reported that wheat-legume rotation improved water-soluble organic carbon (labile carbon) content compared with continuous wheat. Another long-term study conducted at three different sites in Saskatchewan, Canada (Scott, Indian Head, and Melfort) and observed that light fraction carbon (labile carbon) content was the greater in continuous cropping and lower in treatments with frequent summer fallow, but it reflected the short-term influence owing to its short-lived characteristics (Janzen et al., 1992).

2.4.4 Soil Bulk Density (BD)

Soil bulk density is an important index of soil compaction. Soil BD depends on soil texture, structure and moisture, soil particles packing arrangement as well as soil management. A long-term study for three years conducted in Cerrado (Brazilian tropical savanna) in ICLS under no-till treatment showed that the soil bulk density was reduced

and the soil compaction was relieved in the ICLS due its positive impacts on soil total porosity and the lower penetration resentence at 0- to 20- cm depth (Costa et al., 2015a). A 2-year study involving two grazing treatments (grazed and un-grazed) in Florida on an Ultisol, Dothan sandy loam, (George et al., 2013) concluded that grazing significantly impact on soil BD only at 0- to 5- cm depth, little differences were detected at depths lower than 5 cm. Similar results were documented in Australia that livestock grazing did not adversely impact the soil BD, compaction may happen at the soil surface depth when the soil near the saturated point (George et al., 2013; Nie et al., 2016). However, A long-term (3-year) minirhizotron study conducted near Pana, IL to evaluate the soil compaction and crop yield under ICLS, Tracy and Zhang (2008) observed that soil has slightly compaction at 0- to 5- cm depth in the grazed soils, but the root growth did not affect by livestock grazing. A study conducted in Argentina on a silty loam Typic Argiudoll and a sandy loam Typic Hapludoll to estimate the topsoil compaction and recovery in integrated no-tilled crop–livestock systems, Fernández et al. (2015)reported that livestock trampling may lead to soil copmpaction at shallow depths during their grazing period, but that's not a huge damage which can be recovered after removing out the livestock. Livestock grazing winter residues and weeds or covercrop did not significantly increase the BD. Commenly, soil physical state under grazing system might be getting better after a whole winter self-repairing, which might be due to the soil inherent characteristics, such as soil organic carbon content, the percentage of soil moisture and texture, not related to grazing treatment. The property was that the soil had stronger self-healing ability than the soil demage degree (Fernández et al., 2015). However, a study conducted in North China with different grazing intensities reported

that the soil BD was related to grazing intensity, they saw that the high grazing intensity and un-grazed treatments had significantly higher ($P < 0.05$) soil BD values when compared with light grazing intensity and moderate grazing intnesity treatments (Jiao et al., 2016). Soil water retetion as one of the most important soil hydroulic properties, it plays a great role in bulding soil quality (Klute, 1986). The soil volumetric water content fluctuated with seasons and linked with soil temperature, soil BD, and soil organic matter content (George et al., 2013). Davinic et al. (2013) stated that ICLS had the potential ability to improve the soil organic matter content, nutrient cycling, and water retention capacity as compared with single cropping system.

2.4.5 Wet Soil Aggregate Stability (WAS)

Aggregate stability includes dry soil aggregate stability (DAS) and wet soil aggregate stability (WAS), which plays a great role in maintaining and improving soil quality and agricultural sustainability. It refers to the ability of soil aggregates to resist outside force disruption, the DAS usually related to wind erosion and the WAS commonly associated with water erosion (Amezketa, 1999). A long-term (40-year) study conducted by Six et al. (2002) in southwest France on thick humic loamy soils (Vermic Haplubrepts) reported that soil aggregate stability increased with increasing soil organic matter inputs which result in lower the soil particles wettability and improve the cohesion of aggregates. However, another study conducted by Abiven et al. (2009) documented that there was no direct relevance or connection between organic matter inputs and aggregate stability dynamics. Finding from west Texas reported that under continuous cotton and perennial pasture treatments, continuous cotton treatment lowered the soil aggregate stability than that of perennial pasture treatment under ICLS (Acosta-Martínez

et al., 2004a). A 3-year study in USA with different ecoregions demonstrated that the soil WAS value was not significantly affected by cattle grazing at soil surface depth (0- to 6-cm) (Sulc and Franzluebbers, 2014). However, different conclusion was given by Nie et al. (2016) that light to moderate grazing intensities were beneficial for WAS as a result of the improved root growth and expansion.

2.4.6 Microbial Biomass Carbon/Nitrogen

Soil microbial biomass is one of the most critical biological parameters which is sensitive to short-term soil management changes (Ghani et al., 2003). Microbial biomass carbon and nitrogen are the labile fraction of the soil organic matter and treat as the important source of food energy and nutrients for crop growth (Ajwa et al., 1999; Garcia and Rice, 1994; Jenkinson, 1981). Microbial carbon concentration improved with the starting of the grazing till in September, after that the microbial carbon concentration started to decrease with the crops or the pasture fading. However, the microbial nitrogen content decreased during the same period, it may due to the N in soil was supplied to the crops for growth. An experiment conducted on an Oxisol (Latosol) in southern Brazil, illustrated that the ICLS with adequate grazing intensity under no-tillage management and no-tillage systems without grazing treatment brought the same effects on maintaining soil biological quality (Souza et al., 2010). Crop diversity and grazing impact on soil microbial biomass. Acosta-Martínez et al. (2004a) concluded that soil microbial biomass carbon content was 113 mg kg^{-1} higher in the rotation under rye and cotton than that in continuous cotton at 0- to 5- cm depth. Similar trend was found in soil microbial biomass nitrogen. Some researches revealed that microbial biomass carbon content declined with the growing grazing intensity (Acosta-Martínez et al., 2010; Liu et al., 2012; Northup et

al., 1999). Irrigation conditions have influence on the microbial biomass carbon content in ICLS as well. Data from the study conducted by George et al. (2013) showed that grazing increased microbial biomass carbon by 2 to 2.5 times up to 15- cm depth compared with un-grazed plots under non-irrigated systems.

2.4.7 Urease Enzyme Activity

Soil enzyme activity could be used as a sensitive index in maintaining soil biological diversity as it influenced by soil management practices (Ajwa et al., 1999). Dormaar et al. (1984) stated that in a 3-year study of blue grama (*Bouteloua gracilis*), most of the residue was decomposed and remained quite few residues during October to next May. A study conducted on 21 types of Iowa soils at the surface depth, urease activity was significantly related to organic C (r = 0.72***), total N (r = 0.71***), and cation-exchange capacity (r = 0.67***), as well as related to clay (0.53*), sand (−0.47*), and surface area (0.45*). Among all the soil parameters, organic matter content had the highest connection with urease activity (Zantua et al., 1977). Acosta-Martínez et al. (2004) documented that microbial biomass C and enzyme activities in grazed plots was greater than un-grazed plots under ICLS in Texas study. It was also reported that soil enzyme activities were increased under the rye-cotton compared with that under continuous cotton at 0- to 5- cm depth (Acosta-Martínez et al., 2004a). Many soil nutrients cycling do not exist and process without the soil microorganisms, which are related to the decomposition process of crop residue.

2.4.8 Beta-glucosidase Enzyme Activity

Beta-glucosidase was considered as an effective indicator that reflect the soil management changes, and hence it has an important role in carbon cycling (Bandick and

Dick, 1999). There was no relevance between enzymes activities and soil organic content, and enzyme activity and total microbial biomass was observed by Badiane et al. (2001). Grazing and crop diversity have significant effect on beta-glucosidase enzyme activity. It was detected that grazing increased the beta-glucosidase activities by 23 mg p-nitrophenol kg soil^{-1} h^{-1} compared with that under un-grazed soils at the soil surface depth (George et al., 2013). A long-term study processed in Breton, French on a Gray Luvisolic soil under a wheat-fallow and a wheat-oats-barley-forage-forage rotation, reported that microbial biomass and enzyme activities were greater under wheat-oats-barley-forage-forage rotation than that under wheat-fallow rotation (McGill et al., 1986).

2.5 Research Gap

There is lack of information on the impacts of ICLS on soils properties in North Dakota, USA. Many of the related studies were conducted in other states or countries with different types of soil and the crop rotation. Therefore, based on North Dakota special soil and weather condition, a five-year rotation compared to continuous spring wheat (control treatment) under ICLS study was designed to evaluate the soil chemical, physical, hydrological, and biological properties response to the ICLS.

CHAPTER 3

MATERIALS AND METHODS

3.1 Experimental Location and Design

The study site initiated in 2010 at the Dickinson Research Extension Center located near Dickinson, North Dakota (46˚53'N, 102º49'W). The site consists of 18 uniform rectangular 1.74 ha (31.3 ha in total) plots. This experimental site was established to investigate the soil quality response to the application of the integrated beef cattle and crop production system. Soils of the study site are Vebar fine sandy loam (Coarse-loamy, mixed, superactive, frigid Typic Haplustolls) and Savage silty clay loam (Fine, smectitic, frigid Vertic Argiustolls). The average annual precipitation of the study site is 408.8 mm and the annual average low temperature is -0.6 ºC and annual average high temperature is 12.9 ºC from 2010 to 2017.

The treatments were laid down in a randomized complete block design (RCBD) with 3 replications. The treatments include six cropping treatments, and two grazing managements (grazed and un-grazed). The cropping treatments are: continuous spring wheat (control, CNT), sunflower (*Helianthus annuus* L.)-spring wheat (*Triticum aestivum* L.)-cover crop-corn (*Zea mays* L.)-pea (*Pisum sativum* L.) & barley (*Hordeum vulgare* L.) (S1), spring wheat-cover crop-corn-pea/barley-sunflower (S2), cover crop-corn-pea/barley-sunflower-spring wheat (S3), corn-pea/barley-sunflower-spring wheat-cover crop (S4), and pea/barley-sunflower-spring wheat-cover crop-corn (S5). The cattle grazing occurs in every rotation except the continuous spring wheat. The exclusions areas were developed in 2016 for comparing the data between grazed and un-grazed. Based on crop growth, field pea-barley reached grazing condition first and grazing started on July

20, 2016 for 27 grazing days (0.218 ha·steer^{-1}). MasterGraze grazing corn attained grazing condition by August 16, 2016, when yearling steers rotated from field pea-barley to the MasterGraze corn for 50 grazing days (0.131 ha· steer^{-1}) and then rotated to the 13-species cover crop for 28 grazing days (0.218 ha· steer^{-1}). The winter triticale and hairy vetch were planted in the fall of 2010 for the spring of 2011 hay harvest, when it started the experiment. For the cover crop year, harvest begins with windrowing and round baling winter triticale-hairy vetch hay mid-June. After bale removal, yearling steers subsequently grazed a 13-species cover crop planted 2.54 cm deep in 19.05 cm rows. Spring wheat plant population of 506,073 plants/ha was seeded 3.81 cm deep in 19.05 cm rows. Forage corn (*Zea mays,* Pioneer 39N99 (*var*.)) was planted 5.08 cm deep using a plant population of 7,692-8,097 plants/ha in 0.76 m rows. Field pea-barley (*Pisum sativum, var. Arvika* and *Hordeum vulgare, var. Stockford)* was seeded at the rate of 67.2 kg/ha and Stockford (*var*.) forage barley was seeded at 44.8 kg/ha. Sunflower (*Helianthus annuus* L.) was also planted 5.08 cm deep using a plant population of 7,692-8,097 plants/ha in 0.76 m rows. A John Deere 1590 no-till drill with 19.1 cm row spacing facilitated corn planting and a John Deere 7000, no-till 6-row planter set at 0.76 m row spacing facilitated sunflower planting.

3.2. Sample Collection

Intact core samples were collected on June 11, 2016 from all the plots at 0-5 cm with core sampler which has 5 cm diameter and 5 cm height core for the bulk density and water retention analyses. In addition, soil samples were also collected from 0- to 5-, 5- to 15-,15- to 30-, 30- to 45-, and 45- to 60- cm depths using a soil auger. Soil samples were also collected on April 14, 2017, except the intact core samples were collected in June

2017. Samples were collected from 9 plots inside and outside of exclusion cages to represent un-grazed and grazed areas, respectively.

3.3 Laboratory Analysis

3.3.1 Soil Bulk Density

Soil bulk density for all the samples collected from 0- to 5-, 5- to 15-,15- to 30-, 30- to 45-, and 45- to 60- cm depths was determined by dividing the soil dry mass with the known soil volume (Grossman and Reinsch, 2002). Soil samples were oven dried at 105 ºC for at least 48 hours to get the soil dry mass.

3.3.2 Soil pH and Electrical Conductivity (EC)

Soil samples for the 0- to 5-, 5- to 15-,15- to 30-, 30- to 45-, and 45- to 60- cm depths were air dried, grounded, and sieved to pass through a 2-mm sieve. A total of 10 g of soil was placed in a centrifuge tube and added 10 mL of distilled water (the ratio of soil and water is 1:1), stirred the suspension with vortex mixer for 30 seconds, and then pH meter was used to measure the soil pH (Kalra, 1995). After measuring the soil pH, 15 mL of distill water was added to the sample (the ratio of soil and water is 1:2.5), mixed the suspension and tested for the EC using the EC meter.

3.3.3 Soil Water Retention (SWR)

Cheesecloth was fixed at the bottom of the intact cores with the rubber band, then the soil core was saturated with water for 1 to 3 days depending on the soil type. Soil water retention was measured with the method described by Klute and Dirksen (1986). It was measured at seven different matric potentials; 0, -0.4, -1.0, -2.5 and -5 kPa in the tension table and at -10 and -30 kPa in ceramic pressure plate.

3.3.4 Soil Wet Aggregate Stability (WAS)

For the WAS, only the top two depths (0- to 5- and 5- to 15- cm) were analyzed. The WAS content was measured using the method described by Kemper and Rosenau (1986). A 3 g of 1-2 mm (sieved between 2 and 1 mm sieves) air-dry soil in a sieve was saturated with cold vapor machine, then transfer to shaking slots for 5 minutes to get unstable aggregates and using the sonicator to break down the remaining soil particles to get the stable aggregates. Then, the soil suspension was kept in the oven to dry overnight at 105 ºC to get constant weight. The percentage of soil stable aggregate was calculated by dividing the oven dry stable aggregates with the stable and unstable aggregates weight.

3.3.5 Soil Organic Carbon (SOC) and Total Nitrogen (TN)

Soil organic carbon concentration was determined using the CN elemental analyzer. The percentage of total carbon (TC) and TN can was obtained from the CN elemental analyzer. Soil inorganic carbon was determined for all the soil samples by the reaction with hydrochloric acid (Schumacher, 2002). The SOC was calculated by subtracting the soil inorganic carbon from total carbon.

3.3.6 Soil Carbon and Nitrogen Fraction

Carbon and nitrogen fractions (labile, stable, and inert) were analyzed using cold water, hot water and acid extraction methods (Ghani et al., 2003; Silveira et al., 2008). To determine labile carbon fraction which is the cold-water extracts (CWE), a 3-g soil was placed into 50 mL polypropylene centrifuge tubes with 30 mL of distilled water. Soil suspension was mixed thoroughly on vortex mixer for 10 seconds and then moved to an end-over-end shaker for 30 minutes at 40 rpm. After that, the suspension was centrifuged

at 3000 rpm for 25 minutes, and supernatant was separated from soil by using 0.45 µm pore size syringe filters. Soil remained after separating the supernatant was used to determine stable carbon fraction. 30 mL of distilled water was added in each tube and mixed with vertex mixer for 10 seconds. Keeping tubes in hot water bath at 80ºC for 12 hours, and then these tubes were centrifuged at 3000 rpm for 25 minutes and the supernatant was filtered using 0.45 µm pore size syringe filters and named as hot water extracts (HWE). Following the hot water extraction process, soil left in the tube was kept air dried and pending for the inert fraction of carbon analysis. Taking 0.5 g of soil and adding 15 mL of 1M HCl and heating at 105ºC for 12 hours, then, tubes were centrifuged at 3000 rpm for 25 minutes and the supernatant was filtered using 0.45 µm pore size syringe filters. Again 15 mL of 6M HCl was added to soil left in the soil and hydrolyzed for 12 hours at 105ºC, centrifuged at 3000 rpm for 25 minutes and the supernatant was filtered using 0.45 µm pore size syringe filters and termed as Acid Extracts (ACE). Meanwhile, the nitrogen fraction can be decided as well. These total carbon and nitrogen were considered as organic carbon and organic nitrogen in each extract by considering no inorganic carbon in soil as the pH of the soil was less 6. Cold-water, hot-water, and acid extraction carbon and nitrogen were determined for 0- to 5- and 5- to 15- cm depths using the TOC-L analyzer (Shimadzu Corporation, model-TNM-L-ROHS).

3.3.7 Microbial Biomass Carbon (MBC) and Nitrogen (MBN)

The MBC and MBN were determined by chloroform fumigation direct extraction method (CFDE) (Beck et al., 1997; Carter, 1993). Each sample was divided into 3 subsamples: one for determining the gravimetric soil moisture content (drying the soil 48 hours at 105 ºC); one non-fumigated sample (10 g oven-dry equivalent) for immediate

extraction with 0.5M potassium sulfate (K_2SO_4); and one fumigated sample (10 g oven - dry equivalent). The non-fumigated subsample was placed in a centrifuge tube with 40 mL of 0.5 M K_2SO_4. After shaking the sample on shaker for one hour, it was filtered through pre-leached (with 0.5 M K_2SO_4) Whatman No. 1 filter paper, and then the extract was kept at 4 ºC until further analysis.

The samples those need to be fumigated were kept in 50 mL glass beakers and kept in a vacuum desiccator with a 50-mL beaker containing boiling chips and 20 mL of chloroform in it. All the samples were kept in vacuum until the chloroform boils. Then the samples were kept in dark for 24 hours (chloroform easily decomposed in light). After releasing the vacuum and excess chloroform, the soil sample was extracted with 40 mL of potassium sulfate and shook for 1 hour, then, filter through Whatman no. 1 filter paper and the extract was stored for further analysis. The total dissolved carbon content was determined on a TOC-L analyzer (Shimadzu Corporation, model-TNM-L-ROHS). The difference between C in the fumigated and non-fumigated samples is the chloroform - labile C pool (EC), and is proportional to microbial biomass C (C):

$$C = EC/kEC$$

where kEC is soil specific, but is often estimated as 0.45 (Beck et al., 1997).

Determination of the microbial biomass C and N.

Total weight of extractable C in the fumigated (C_F) and unfumigated (C_{UF}) soil samples:

C_F, C_{UF} (µg g^{-1} soil) = organic C * [(WT - DW) + EV] / DW

Total weight of extractable N in the fumigated (N_F) and unfumigated (N_{UF}) soil samples:

N_F, N_{UF} (µg g^{-1} soil) = total N * [(WT - DW) + EV] / DW

Where WT is the soil fresh weight, DW is the soil dry weight, EV is extractant volume

Microbial biomass C in the soil (MBC):

MBC (µg g^{-1} soil) = (C_F - C_{UF}) / K_{EC}

Where K_{EC} = 0.35 and represents the efficiency of extraction of microbial biomass C. Values for K_{EC} range from 0.25 to 0.45 (Joergensen and Mueller, 1996; Wu et al., 1990).

Microbial biomass N in the soil (MBN):

MBN (µg g^{-1} soil) = (N_F - N_{UF}) / K_{EN}

where K_{EN} = 0.5 and represents the efficiency of extraction of microbial biomass N. Values for K_{EN} range from 0.18 to 0.54 (Joergensen and Mueller, 1996)

3.3.8 Beta-glucosidase Enzyme

Beta-glucosidase enzyme activity was determined with the method describe by Eivazi and Tabatabai (1988). Briefly, a calibration curve developed with standards containing 0, 100, 200, 300, 400, or 500 nmol of p-nitrophenol in each flask. 1 g of soil was taken separately in three 50 mL Erlenmeyer flasks (one is control) and 0.2 mL of toluene was added, mixed, and let them set for 15 minutes in a fume hood. Then 4 mL of modified universal buffer (MUB) pH 6.0 and 1 mL of p-nitrophenyl-β-D-glucoside (PNG) solution were added, mixed thoroughly, and incubated the soil suspension at 37˚C for 1h. After that, 1 mL of 0.5M Calcium Chloride ($CaCl_2$), and 4 mL of 0.1M Tris (hydroxyethyl) Aminomethane (THAM) buffer (pH 12) were added and mixed thoroughly, and the suspension was filtered through a Whatman No.2V folded filter paper. The yellow color intensity of the filtrate was determined with a spectrophotometer at 405 nm and the amount of p-nitrophenol released by reference to a calibration curve was calculated. Beta-glucosidase enzyme activity was expressed as µg p-nitrophenol kg^{-1} soil. Control should be included for each assay by following procedure described above,

but adding the substrate PNG solution after termination of the reaction using THAM buffer (pH 12). The amount of p-nitrophenol released from the soil was determined by using reference to calibration curves was calculated using the following equation:

Beta-glucosidase activity (µg p-nitrophenol g^{-1} soil h^{-1}) = (NCS-NCC) *V*T/DW where, NCS is p-nitrophenol content of sample average (µg NH_4-N mL^{-1}), NCC is p-nitrophenol content of control (µg NH_4-N mL^{-1}), V is volume of PNG solution used (1 mL), T is incubation time (1 h), and DW is dry weight of soil taken (1 g).

3.3.9 Urease Enzyme

Urease enzymes activity was determined with colorimetric determination of ammonium method described by Kandeler and Gerber (1988). 5g of fresh soil was placed in three 50 mL flasks separately, and 2.5 mL of urea solution were added in the first two flasks. Then 20 mL of borate buffer was kept in all the flasks. All the flasks were incubated at 37 ˚C for 2 hours. After incubation, 2.5 mL of urea solution was added in the third flask. 30 mL of solution extractor solution (2M Potassium Chloride, KCl) was added to all flasks and shook for 30 minutes. After the filtration process of all the samples, 1 mL of filtrate with 9 mL of water and 5mL of sodium salicylate ($C_7H_5NaO_3$)-sodium hydroxide (NaOH) solution as well as 2 mL of Oxidation agent - sodium dichloroisocyanurate ($C_3Cl_2N_3NaO_3$) was mixed and performed the color reaction for 30 minutes. At last, the absorbance of the soil samples was determined with spectrophotometer at 660 nm wavelengths and a standard curve was prepared with standards of 0, 1, 1.5, 2, and 2.5 µg N mL^{-1} of ammonium chloride (NH_4Cl). Urease activity (µg NH_4-N g^{-1} h^{-1}) was calculated using the following equation:

Urease Activity (µg NH_4-N g^{-1} h^{-1}) = (NCS – NCC) × DF× V× T/DW

where, NCS is the NH_4-N concentration of the sample average (µg NH_4-N mL^{-1}), NCC is the NH_4-N content of the control (µg NH_4-N mL^{-1}), DF is dilution factor (10), V is the volume of urea solution used (2.5 mL), T is incubation time (2 h), and DW is the dry weight of the soil taken (5 g).

3.4 Statistical Analysis

The impacts of cropping sequences system on the selected soil parameters measured in 2016 were analyzed using Analysis of Variance (ANOVA) method using the SAS9.4 (SAS, 2013). The Kolmogorov–Smirnov method was used to test the normality distributions of the datasets. Statistical comparisons of differences in soil pH, EC, BD, WAS, SOC, TN, MBC, MBN among the six cropping treatments and the two grazing treatments for each depth in 2017 were obtained using pairwise differences method to compare least-squares means estimated by a mixed model using the GLIMMIX procedure in SAS 9.4, where the sequence, grazing, and sequence by grazing were considered as fixed effects and replication as random effect. Statistical differences were declared significant at the α=0.10 level.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 pH and Electrical Conductivity

Soil pH and electrical conductivity (EC) data for 0- to 5-, 5- to 15-, 15- to 30-, 30- to 45-, and 45- to 60- cm depths under different cropping sequences and grazing treatments are shown in Table 4.1 through 4.4. Cropping sequences did not impact the pH significantly for any depth in 2016 and 2017 (Table 4.1 and Table 4.2). Soils under CNT (continuous spring wheat, control) had the lowest pH values compared with the other five cropping sequences at the 0- to 5- cm depth in both years, except that cropping sequence 4 (S4) (pH = 5.55) had 3.6% lower value than that of CNT (pH = 5.76) in 2017, however, differences were not significant. Mean pH ranged from 4.98 to 6.47 at 5- to 15- cm depth for 2016. The highest pH was found in cropping sequence 3 (S3) (pH = 5.95) which was 8.8% higher than that of CNT (pH = 5.47) at 5- to 15- cm depth in 2016. Similar trend was observed in 15- to 30- , 30- to 45- and 45- to 60- cm depths in 2016. The pH value of CNT (pH = 5.17) at 5- to 15- cm depth in 2017 was the lowest, and it was 20, 2.5, 16, 2.5 and 2.1% lower than that of cropping sequences 1 (S1), 2 (S2), 3 (S3), 4 (S4), and 5 (S5), respectively. The soil pH value under cropping sequence 3 (S3) were 9.7, 6.5 and 2% higher for the 15- to 30- , 30- to 45- and 45- to 60- cm depths in 2017, respectively, compared with CNT. However, the differences were not statistically significant. Grazing did not influence the soil pH values. In general, soil under grazed treatments were 3.6, 0.4, 0.5, 0.0 and 1.4% lower than un-grazed treatments for 0- to 5-, 5- to 15-, 15- to 30-, 30- to 45- and 45- to 60- cm depths, respectively, however, differences in pH values were not statistically significant. The interactions of cropping sequences by grazing were non-significant for all the depths.

Cropping sequences treatment did not significantly affect EC for any depth in 2016 (Table 4.3). However, cropping sequences significantly influenced the soil EC at 5- to 15- cm depth in 2017 (Table 4.4). The mean value of EC ranged from 0.103 to 0.161 dS m^{-1} at 5- to 15- cm depth in 2017. The EC under cropping sequence 3 (S3) (0.161 dS m^{-1}) was 36, 3 and 3% higher than that of CNT and cropping sequences 4 (S4) and 5 (S5) (0.103, 0.111 and 0.111 dS m^{-1}), respectively, however, differences were not significant. Grazing did not have significant effect on soil EC for any depth for 2017. It was observed that the EC for 0- to 5- and 5- to 15- cm depths were 28 and 12.5% higher under grazed treatment (0.220 and 0.135 dS m^{-1}, respectively) than the un-grazed treatment (0.172 and 0.120 dS m^{-1}, respectively), whereas, EC values for 15- to 30-, 30- to 45- and 45- to 60- cm depths were 7.5, 8.1 and 11.9% lower under grazed treatment (0.149, 0.181 and 0.214 dS m^{-1}, respectively) than the un-grazed treatment (0.161, 0.197 and 0.243 dS m^{-1}, respectively), but the differences were not statistically significant. The interactions between cropping sequences and grazing were not statistically significant at any depth.

4.2 Soil Bulk Density

Data on the soil bulk density (BD) under different cropping sequences and grazing treatments in 2016 and 2017 for the 0- to 5-, 5- to 15-, 15- to 30-, 30- to 45- and 45- to 60- cm depths are summarized in Table 4.5 and 4.6. The BD values under six different cropping sequences were not significantly different in 2016 at the 0- to 5- cm depth. The mean BD in the cropping sequence 3 (S3) (1.10 Mg m^{-3}) at the 0- to 5- cm depth was numerically 12% lower than that of CNT (control treatment-continuous spring wheat) (1.25 Mg m^{-3}). The mean value of BD in cropping sequence 5 (S5) (1.07 Mg m^{-3}) was numerically 14.4% lower than that of CNT. The cropping sequence 1 (S1) (1.35 Mg

m^{-3}) had the highest BD value among the six different cropping sequences at the 0- to 5-cm depth. However, the differences were not significant. In 2017, cropping sequences did not impact soil BD at any depth except at the 30- to 45- cm depth where BD was significantly lower under cropping sequence 4 (S4) (1.26 Mg cm^{-3}) compared to the control (Table 4.6). Grazing treatment significantly impacted the BD only at the 0- to 5-cm depth in 2017. The mean BD in the grazing plots (1.29 g cm^{-3}) was significantly higher than that for the un-grazed treatment (1.28 g cm^{-3}). The interactions of cropping sequences by grazing were not significant at any depth. Similar result of grazing effects on BD was reported by George et al. (2013) who showed that BD was significantly impacted by grazing only for the 0- to 5- cm depth. Moreover, another study reported that only the surface depth soils can be compacted by cattle grazing, especially when the soil moisture was higher (Nie et al., 2016). However, different results from a researcher in Argentina was reported that the cattle grazing did not cause the soil compaction problem in integrated no-till crop-livestock system (Fernández et al., 2015).

4.3 Soil Organic Carbon and Total Nitrogen

Soil organic carbon (SOC) and total nitrogen (TN) data for the 0- to 5-, 5- to 15-, 15- to 30-, 30- to 45-, and 45- to 60- cm under six different cropping sequences and two grazing treatments are presented in Table 4.7 through 4.10. In 2016 and 2017, the cropping sequences treatments not significantly influenced the SOC content in any depth. For these two years, SOC values in cropping sequence 3 (S3) (32.1 g kg^{-1} and 33.8 g kg^{-1}, respectively) at the surface depths were higher than those under CNT (23.2 g kg^{-1} and 23.5 g kg^{-1}, respectively), which is the control treatment - continuous spring wheat, however, the differences were not statistically significant. The cropping sequence 3 (S3)

(cover crop-corn-pea/barley-sunflower-spring wheat) soils had the highest SOC value followed by those of cropping sequence 2 (S2) (spring wheat-cover crop-corn-pea/barley-sunflower), cropping sequence 4 (S4) (corn-pea/barley-sunflower-spring wheat-cover crop), cropping sequence 5 (S5) (pea/barley-sunflower-spring wheat-cover crop-corn), cropping sequence 1 (S1) (sunflower-spring wheat-cover crop-corn -pea/barley) and CNT (continuous spring wheat) at 0- to 5- cm depth in 2016, which means cropping sequences increased SOC, but no statistically significant differences in SOC values were observed among the six cropping sequences (Table 4.7). The concentration of SOC decreased with increasing depth up to 30 cm in 2016. Among the six cropping sequences in 2017, similar to 2016, the highest SOC value was observed in cropping sequence 3 (S3) (33.8 g kg^{-1}) at 0- to 5- cm depth, which was numerically 44% higher than that of CNT (23.5 g kg^{-1}). Similar trends were found in the other depths; however, differences were non-significant. The SOC was not significantly affected by grazing treatment in 2017 for 0- to 60- cm depth (Table 4.8). Similar result was reported in Tibet, China that short term grazing did not impact soil properties including SOC up to 30 cm depth (Lu et al., 2015). However, another study found higher SOC in grazed plots compared with un-grazed plots in 2010, but this trend was reversed in 2011 that un-grazed plots had higher SOC instead of grazed plots (George et al., 2013). The cropping sequences and grazing interaction for SOC was non-significant for all the depths.

Data for TN of different treatments in 2016 and 2017 are represented in Table 4.9 and 4.10. Cropping sequences treatment did not significantly impact TN in 2016. The CNT had the lowest TN value compared with the other cropping sequences for all depths in 2016, except cropping sequence 1 (S1) at 0- to 5- cm depth (Table 4.9), however, the

differences were not significant. The average value of TN ranged from 0.77 to 2.49 g kg^{-1} at 0- to 60- cm depth in 2016. The TN content values decreased with increasing depth. TN values under cropping sequence 4 (S4) were 4.8, 5.7, 29, 15, and 17% numerically higher for the 0- to 5-, 5- to 15-, 15- to 30-, 30- to 45- and 45- to 60- cm depths, respectively, compared with CNT (control treatment- continuous spring wheat). In 2017, the TN content was not influenced by cropping sequences at all the depths (Table 4.10). The highest value as observed under cropping sequence 4 (S4) (2.49 g kg^{-1}) at 0- to 5- cm depth, where it was 12% higher than that of CNT, however, differences were not statically significant. In both years, in general, TN content was lower for CNT (continuous spring wheat) than the other five cropping sequences (cropping with different crops) even though the differences in TN values were not statistically significantly. In a 5-year experiment involving continuous cotton and an integrated livestock-crop system with two stages of a cropping sequences (wheat [*Triticum aesticum*]-fallow-rye [secale cereale]-cotton) on a Pullman soil (Fine, mixed, thermic Torrertic Paleustolls). It was observed that TN content was no difference under all the treatments (Acosta-Martínez et al., 2004b). Grazing did not significantly impact the TN for any depth. However, one study conducted that grazing increased TN content due to introducing cattle in the integrated crop-livestock system (George et al., 2013). The interactions of cropping sequences by grazing on TN were not statistically significant for any depth.

4.4 Wet Soil Aggregate Stability

The wet soil aggregate stability (WAS) data for the 0- to 5- cm and 5- to 15- cm depths under six different cropping sequences and grazing treatments are presented in Table 4.11 and 4.12. The soil WAS values were not significantly affected by cropping

sequences for the 0- to 5- and 5- to 15- cm depths. For 0- to 5- cm depth, the WAS of cropping sequence 2 (S2) were 97.2 and 96.4% in 2016 and 2017, respectively, which were 10 and 13% higher than those of CNT (88.3 and 85.2%, respectively), although the differences were non-significant. Little difference was found at 5- to 15- cm depth in both years, either. Grazing did not impact on WAS for 0- to 5- and 5- to 15- depths in 2017. The soil WAS mean was 5% higher for grazed treatment at the surface depth, while not statistically significantly different, and beyond 5- cm depth, the WAS value was almost the same.

A similar study conducted on Ultisols in Georgia, USA documented that soil aggregation stability was similar between the grazed treatment and un-grazed treatment in the first three grazing years (Sulc and Franzluebbers, 2014). Another study reported in Australia that lower grazing intensity improved the soil aggregate stability due to the root growth development, while higher grazing intensity lowered the aggregate stability as the animal trampling break down the soil aggregates (Nie et al., 2016).

4.5 Soil Carbon and Nitrogen Fractions

Data for soil labile carbon, stable carbon, inert carbon (1M and 6M HCl extractable carbon) of different cropping sequences and grazing treatments for 0- to 5- and 5- to 15- cm depths and are shown in Table 4.13 through 4.20. Cropping sequences did not impact soil labile carbon at 0- to 5- and 5- to 15- cm depths in 2016 and 2017. It was observed that grazing treatment did not significantly influence the soil labile carbon, either. The average of labile carbon content ranged from 14.0 to 27.3 μg g^{-1} and 18.8 to 33.3 μg g^{-1} for 0- to 15- cm depth in 2016 and 2017, respectively. The labile carbon concentration decreased with increasing depth in both years. The labile carbon values

under grazed treatment (28.5 and 19.9 µg g^{-1}, respectively) were numerically 5 and 2 % higher for the 0- to 5- and 5- to 15- cm depths, respectively, compared with the un-grazed treatments (29.9 and 20.2 µg g^{-1}, respectively) in 2017. No interaction between cropping sequences and grazing on soil labile carbon was observed in 2016 and 2017. Data on soil stable carbon showed that no significant difference among the six cropping treatments for both depths. The cropping sequence 3 (S3) had the highest soil stable carbon compared with the other five cropping sequences at 0- to 5- and 5- to 15- cm in 2016, which were 18 and 21% higher those of CNT (Table 4.13 and 4.14), although non-significant statistically difference. Similar trend for soil stable carbon was found at 5- to 15- cm depth in 2017 (Table 4.16). Grazing did not significantly impact soil stable carbon for both depths. Grazing decreased soil stable carbon for 4% at 0- to 5- cm depth in 2017 compared with un-grazed treatments, whereas grazed treatment (73.3 µg g^{-1}) was higher than that of un-grazed treatment (76.2 µg g^{-1}), however, the differences were not statistically significant. In a 2-year experiment consist of different grazing intensities on allophanic soil in New Zealand showed that the intensively grazed dairy pasture always had lower soil stable carbon content than the sheep and beef/cattle grazed pasture (less grazing intensive) (Ghani et al., 2003). The interaction of cropping sequences by grazing was not significantly different for soil stable carbon on any soil depth in 2017. Data for 1M and 6M HCl extractable inert carbon did not show any significant difference at 0- to 5- and 5- to 15- cm depths. The inert carbon (1M HCl extractable carbon) ranged from 195.9 to 355.0 µg g^{-1} at 0- to 5- cm depth and 136.9 to 297.9 µg g^{-1} at 5- to 15- cm depth in 2016. The inert carbon (6M HCl extractable carbon) ranged from 72.3 to 139.2 µg g^{-1} at 0- to 5- cm depth and 45.9 to 74.1 µg g^{-1} at 5- to 15- cm depth in 2016. The interaction

of cropping sequences by grazing was non-significant different. In both years, in general, the soil labile, stable, and inert carbon (1M and 6M) content decreased with increasing depth, but did not impacted by cropping sequences, grazing, and cropping sequences by grazing.

Data for soil labile nitrogen, stable nitrogen, inert nitrogen (1M and 6M HCl extractable nitrogen) of different cropping sequences and grazing treatments for 0- to 5- and 5- to 15- cm depths and are shown in Table 4.17 through 4.20. Cropping sequences did not impact soil labile nitrogen at 0- to 5- and 5- to 15- cm depths in 2016 and 2017. The mean of soil labile nitrogen ranged from 1.58 to 4.34 μg g^{-1} at 0- to 15 cm depth in 2016. The soil labile nitrogen values reduced with increasing depth in 2016 (Table 4.17). Cropping sequence 5 (S5) had the highest soil labile nitrogen concentration at 0- to 5- and 5- to 15- cm depths in 2016, which were 40 and 12% higher than that of CNT, however, the differences were not significant. In 2017, among all the cropping sequences, highest soil labile nitrogen value was observed in cropping sequence 3 (S3) (2.19 and 1.04 μg g^{-1}) at 0- to 5- and 5- to 15- cm depths, respectively, which were 45 and 9 % higher than those of CNT (1.51 and 0.95 μg g^{-1}), however, differences in soil labile nitrogen values were not statistically significant. It was observed that grazing treatment did not significantly influence the soil labile nitrogen, either. Mean labile nitrogen content ranged from 0.76 to 2.19 μg g^{-1} for 0- to 15- cm depth in 2017. The labile nitrogen concentration decreased with increasing depth in both years. The labile nitrogen values under grazed treatment were 15 and 5 % higher for the 0- to 5- and 5- to 15- cm depths, respectively, compared with the un-grazed treatments (Table 4.19 and 4.20), however, the differences were not significant. No interaction between cropping sequences

and grazing on soil labile nitrogen was observed in 2016 and 2017. Cropping sequences did not influence the soil stable nitrogen significantly among the six cropping treatments for both depths. The cropping sequence 3 (S3) had the highest soil stable nitrogen compared with the other five cropping sequences at 0- to 5- cm in 2016 and 2017, which were 15 and 33% higher those of CNT, although non-significant statistically difference. Grazing did not significantly impact soil stable nitrogen for both depths, either. Grazing decreased soil stable nitrogen for numerically 3% at 0- to 5- cm depth in 2017 compared with un-grazed 1.50 µg g^{-1}). The interaction between cropping sequences and grazing was not significant different for soil stable nitrogen for any depth in 2017. Data for 1M and 6M HCl extractable inert nitrogen did not show any significant difference at 0- to 5- and 5- to 15- cm depths in both years. The average of inert nitrogen (1M HCl extractable nitrogen) values ranged from 35.2 to 65.3 µg g^{-1} at 0- to 5- cm depth and 19.4 to 41.3 µg g^{-1} at 5- to 15- cm depth in 2016. The mean of inert carbon (6M HCl extractable carbon) contents ranged from 12.8 to 26.5 µg g^{-1} at 0- to 5- cm depth and 8.67 to 14.7 µg g^{-1} at 5- to 15- cm depth in 2016. The interaction of cropping sequences by grazing was non-significant different. In both years, in general, the soil labile, stable, and inert nitrogen (1M and 6M) content decreased with increasing depth, but did not impact by cropping sequences, grazing, and cropping sequences by grazing.

4.6 Soil Microbial Biomass Carbon and Nitrogen

The soil microbial biomass carbon (MBC) and soil microbial biomass nitrogen (MBN) data for the 0- to 5- cm depth under six different cropping sequences and two grazing treatments are summarized in Table 4.21 and 4.22. The cropping sequences did not significantly influence the MBC activity for 0- to 5- cm depth in 2016. For 0- to 5-

cm depth, the MBC of cropping sequence 3 (S3) (573.5 mg kg^{-1}) was the highest value among all the cropping treatments, which was numerically 65% higher than that of CNT (347.6 mg kg^{-1}) in 2016, but no significant difference. Little difference for MBC was detected among cropping sequences at 0- to 5- cm depth, either. Grazing did not significantly impact on MBC for 0- to 5- cm depths in 2017. The soil MBC value was 3% higher for un-grazed treatment for the surface depth, while not statistically significantly different. A 2-year study stated that, the MBC was higher under grazed treatment when the soil was not irrigated (George et al., 2013). Some other studies reported that the MBC activity decreased with the increasing grazing intensity (Acosta-Martínez et al., 2010; Liu et al., 2012). The MBN data showed that cropping sequences did not significantly affect the MBN activity at 0- to 5- cm depth in 2017, however, the cropping sequences with different crops increased the MBN activity compared with the CNT, which was the control treatment – continuous spring wheat, even though the difference was not significant. Grazing did not statistically influence the MBN activity, but it did improve the MBN activity by 10 % compared with un-grazed treatment.

4.7 Urease and Beta-glucosidase

The urease and beta-glucosidase activity data for the 0- to 5- cm depth under six different cropping treatments and two grazing treatment were presented in Table 4.23 and 4.24. Data showed that cropping sequences and grazing treatments did not impact the amount of urease activity. In 2016, cropping sequences not significantly impact the urease at the 0- to 5- cm depth. However, some differences were observed among six cropping treatments. Urease activity under cropping sequence 4 (S4) had the highest value (160.4 µg N g^{-1} soil h^{-1}) compared to the other cropping treatments. The urease

value in cropping sequence 4 (S4) (160.4 µg N g^{-1} soil h^{-1}) was 7.4% higher than that of CNT (149.3 µg N g^{-1} soil h^{-1}), which is the control treatment-continuous spring wheat. For the urease activity value in the other four cropping sequences, all mean values were numerically lower than that of CNT (149.3 µg N g^{-1} soil h^{-1}). However, the urease activity of CNT in 2017 was the lowest amount among the six cropping treatments, which was 31, 37, 36, 40 and 17% lower than those of cropping sequences 1 (S1), 2 (S2), 3 (S3), 4 (S4), and 5(S5), respectively, however, the differences were not significant.

No differences in urease activity were observed between grazing treatments. However, one study conducted in western Texas documented that urease activity was higher in grazed plots than un-grazed plots (Acosta-Martínez et al., 2004a). The urease activity amount was numerically improved in 2017 compared with those of in 2016 for all cropping treatments. The interaction of cropping sequences by grazing on urease activity was non-significant.

The soil beta-glucosidase was not significantly affected by cropping sequences treatments for the 0- to 5- cm depth in 2016 and 2017. In 2016, the average of beta-glucosidase activity of cropping sequence 4 (S4) (91.7 µg PNG g^{-1} soil h^{-1}) was the highest numerically among all the cropping sequences. The beta-glucosidase values of CNT were the lowest in both years, except the value under cropping sequence 5 (S5) treatment in 2016, even though the differences were not significant. Similarly, the beta-glucosidase increased in 2017 compared those in 2016 for all the cropping sequences, however, no differences were found among cropping sequences treatments and CNT was keep the lowest activity value in 2017 although not statistically significant. Grazing did not impact the beta-glucosidase activity in 2017, while grazing improved the beta-

glucosidase activity by 14% compared with un-grazed treatment although no statistically difference. Similar result was reported that grazing treatment had 47% higher beta-glucosidase activity than that of un-grazed treatment (George et al., 2013).

4.8 Soil Water Retention

Data on soil water retention (SWR) for 0- to 5- cm depth under six cropping sequences and two grazing treatments at seven soil water pressures are presented in Table 4.25 and 4.26. No differences were observed for all pressures among all the cropping sequences treatments in 2016. Soil water content for cropping sequence 3 (S3) was higher at the first five soil water pressures (0.0, -0.4, -1.0, -2.5 and -5.0 kPa), but lower at the last two soil water pressures (-10.0 and -30.0 kPa). The soil water content was 5.5, 5.7, 5.2, 4.9 and 4.5% higher under cropping sequence 4 (S4) compared to CNT (control treatment) at -0.0, -0.4, -1.0, -2.5 and -5.0 kPa pressures, respectively, however, differences in soil water content values were not statistically different. At lower pressures (-10.0, and -30.0 kPa), cropping sequence 2 (S2) released numerically more soil water compared to cropping sequence 3 (S3) and CNT (Table 4.25). In 2017, at soil water pressures 0.0, -0.4, -1.0, -2.5 and -5.0 kPa, cropping sequence 4 (S4) had the highest water content compared to the other cropping sequences, while no significant difference in statistically. At lower pressures (-10.0, and -30.0 kPa), CNT had higher water retention among all the cropping treatments, but not significant difference. Grazing did not impact soil water retention for all soil water pressures, at higher pressures (0.0, -0.4, -1.0, -2.5 and -5.0 kPa), grazing had numerically slightly higher water content compared with un-grazed treatment, while at lower pressure (-10.0 and -30.0 kPa), opposite result was observed, un-grazed treatment had numerically higher water retention, however, the

differences were not statistically significant. The interaction of cropping sequences by grazing was not statistically different for all pressures.

Table 4.1. Means of soil pH as influenced by different cropping sequences for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2016.

Treatments		2016 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
				pH		
CNT	SW	5.45[a†]	5.47[a]	6.53[a]	6.93[a]	7.73[a]
S1	PB	5.88[a]	5.44[a]	6.49[a]	7.15[a]	7.78[a]
S2	SF	5.51[a]	4.98[a]	5.87[a]	6.07[a]	7.11[a]
S3	SW	6.29[a]	5.95[a]	6.78[a]	7.44[a]	7.88[a]
S4	CC	5.68[a]	5.56[a]	6.34[a]	7.05[a]	7.23[a]
S5	CR	6.12[a]	5.24[a]	5.86[a]	6.88[a]	7.58[a]
				Analysis of variance *P>F*		
S		0.77	0.87	0.62	0.32	0.77

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.2. Means of soil pH as influenced by different cropping sequences and grazing treatments for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2017.

Treatments		2017 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
				pH		
CNT	SW	5.76[a†]	5.17[a]	6.41[a]	7.10[a]	7.82[a]
S1	SF	6.64[a]	6.47[a]	6.76[a]	7.39[a]	7.71[a]
S2	SW	5.98[a]	5.30[a]	6.30[a]	7.06[a]	7.74[a]
S3	CC	6.31[a]	6.17[a]	7.03[a]	7.56[a]	7.98[a]
S4	CR	5.55[a]	5.30[a]	6.22[a]	6.90[a]	7.24[a]
S5	PB	5.99[a]	5.28[a]	6.33[a]	6.95[a]	7.59[a]
Grazing (G)						
Yes		5.86[a]	5.59[a]	6.50[a]	7.15[a]	7.58[a]
No		6.08[a]	5.61[a]	6.53[a]	7.15[a]	7.69[a]
				Analysis of variance $P>F$		
S		0.4	0.14	0.39	0.55	0.33
G		0.62	0.96	0.85	0.92	0.83
S×G		0.87	0.9	0.89	0.82	0.83

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.3. Means of soil electrical conductivity (EC) as influenced by different cropping sequences for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2016.

Treatments		2016 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		EC (dS m^{-1})				
CNT	SW	0.172[a†]	0.145[a]	0.175[a]	0.164[a]	0.224[a]
S1	PB	0.197[a]	0.106[a]	0.177[a]	0.220[a]	0.222[a]
S2	SF	0.205[a]	0.083[a]	0.119[a]	0.183[a]	0.181[a]
S3	SW	0.159[a]	0.104[a]	0.123[a]	0.233[a]	0.181[a]
S4	CC	0.154[a]	0.131[a]	0.132[a]	0.170[a]	0.148[a]
S5	CR	0.256[a]	0.133[a]	0.122[a]	0.230[a]	0.253[a]
		Analysis of variance $P>F$				
S		0.48	0.55	0.44	0.75	0.35

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.4. Means of soil electrical conductivity (EC) as influenced by different cropping sequences and grazing treatments for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2017.

Treatments		2017 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		EC (dS m^{-1})				
CNT	SW	0.124[a†]	0.103[b]	0.166[a]	0.203[a]	0.250[a]
S1	SF	0.197[a]	0.139[ab]	0.194[a]	0.197[a]	0.244[a]
S2	SW	0.185[a]	0.117[b]	0.186[a]	0.214[a]	0.297[a]
S3	CC	0.229[a]	0.161[a]	0.164[a]	0.181[a]	0.219[a]
S4	CR	0.149[a]	0.111[b]	0.129[a]	0.179[a]	0.193[a]
S5	PB	0.215[a]	0.111[b]	0.142[a]	0.179[a]	0.244[a]
Grazing (G)						
Yes		0.220[a]	0.135[a]	0.149[a]	0.170[a]	0.214[a]
No		0.172[a]	0.120[a]	0.161[a]	0.197[a]	0.243[a]
		Analysis of variance *P>F*				
S		0.23	0.04	0.18	0.98	0.18
G		0.16	0.27	0.65	0.41	0.71
S×G		0.16	0.56	0.77	0.69	0.82

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.5. Means of soil bulk density as influenced by different cropping sequences for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2016.

Treatments		2016 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		----------Bulk Density (Mg m^{-3}) ----------				
CNT	SW	1.25[a†]	1.31[a]	1.33[a]	1.38[a]	1.35[a]
S1	PB	1.35[a]	1.36[a]	1.33[a]	1.27[a]	1.40[a]
S2	SF	1.18[a]	1.39[a]	1.35[a]	1.34[a]	1.34[a]
S3	SW	1.10[a]	1.26[a]	1.19[a]	1.18[a]	1.23[a]
S4	CC	1.17[a]	1.29[a]	1.27[a]	1.37[a]	1.38[a]
S5	CR	1.07[a]	1.32[a]	1.37[a]	1.28[a]	1.23[a]
		Analysis of variance $P>F$				
S		0.4	0.73	0.14	0.19	0.21

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.6. Means of soil bulk density as influenced by different cropping sequences and grazing treatments for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2017.

Treatments		2017 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		----------Bulk Density (Mg m^{-3}) ----------				
CNT	SW	1.10[a†]	1.43[a]	1.39[a]	1.41[a]	1.46[a]
S1	SF	1.26[a]	1.50[a]	1.42[a]	1.30[bc]	1.34[a]
S2	SW	1.11[a]	1.41[a]	1.33[a]	1.42[a]	1.40[a]
S3	CC	1.15[a]	1.34[a]	1.32[a]	1.37[ab]	1.42[a]
S4	CR	1.21[a]	1.39[a]	1.31[a]	1.26[c]	1.39[a]
S5	PB	1.22[a]	1.45[a]	1.39[a]	1.40[a]	1.43[a]
Grazing (G)						
Yes		1.29[a]	1.39[a]	1.35[a]	1.35[a]	1.42[a]
No		1.28[b]	1.43[a]	1.35[a]	1.36[a]	1.40[a]
		Analysis of variance *P>F*				
S		0.48	0.17	0.1	0.01	0.46
G		0.003	0.7	0.49	0.77	0.77
S×G		0.15	0.46	0.88	0.6	0.62

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.7. Means of soil organic carbon as influenced by different cropping sequences for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2016.

Treatments		2016 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		-------Soil Organic Carbon (g kg^{-1}) -------				
CNT	SW	23.2[a†]	16.9[a]	15.3[a]	13.0[a]	13.6[a]
S1	PB	24.9[a]	18.5[a]	15.0[a]	21.3[a]	23.8[a]
S2	SF	26.7[a]	17.9[a]	15.3[a]	16.1[a]	18.3[a]
S3	SW	32.1[a]	23.4[a]	22.1[a]	21.8[a]	16
S4	CC	25.6[a]	18.0[a]	17.6[a]	18.0[a]	17.9[a]
S5	CR	25.1[a]	15.6[a]	11.1[a]	9.79[a]	12.1[a]
		Analysis of variance *P>F*				
S		0.82	0.58	0.43	0.3	0.3

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.8. Means of soil organic carbon as influenced by different cropping sequences and grazing treatments for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2017.

Treatments		2017 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		-------Soil Organic Carbon (g kg^{-1}) -------				
CNT	SW	23.5[a†]	15.0[a]	11.8[a]	9.76[a]	11.1[a]
S1	SF	26.9[a]	19.7[a]	15.8[a]	20.6[a]	18.7[a]
S2	SW	25.7[a]	18.5[a]	15.8[a]	12.7[a]	16.2[a]
S3	CC	33.8[a]	26.7[a]	26.2[a]	21.6[a]	18.2[a]
S4	CR	27.4[a]	18.0[a]	17.0[a]	15.8[a]	15.1[a]
S5	PB	22.9[a]	15.8[a]	11.2[a]	8.76[a]	9.77[a]
Grazing (G)						
Yes		27.2[a]	20.0[a]	17.6[a]	16.6[a]	15.9[a]
No		27.1[a]	19.0[a]	16.6[a]	14.3[a]	14.1[a]
		Analysis of variance *P>F*				
S		0.26	0.18	0.19	0.19	0.2
G		0.65	0.94	0.81	0.57	0.33
S×G		0.86	0.94	0.94	0.55	0.15

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.9. Means of soil total nitrogen as influenced by different cropping sequences for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2016.

Treatments		2016 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		----------Total Nitrogen (g kg^{-1}) ----------				
CNT	SW	2.07[a†]	1.40[a]	1.02[a]	0.86[a]	0.77[a]
S1	PB	2.02[a]	1.54[a]	1.26[a]	1.18[a]	0.90[a]
S2	SF	2.18[a]	1.66[a]	1.35[a]	1.35[a]	1.00[a]
S3	SW	2.17[a]	1.55[a]	1.22[a]	0.99[a]	0.87[a]
S4	CC	2.18[a]	1.48[a]	1.32[a]	1.21[a]	0.90[a]
S5	CR	2.15[a]	1.41[a]	1.07[a]	1.03[a]	0.92[a]
		Analysis of variance *P>F*				
S		0.99	0.93	0.84	0.6	0.93

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.10. Means of soil organic carbon and total nitrogen as influenced by different cropping sequences and grazing treatments for the 0-5, 5-15, 15-30, 30-45 and 45-60 cm depths in 2017.

Treatments		2017 Soil Depths (cm)				
Sequence (S) [§]	*Crop*	0-5	5-15	15-30	30-45	45-60
		----------Total Nitrogen (g kg^{-1}) ----------				
CNT	SW	2.18[a†]	1.46[a]	1.13[a]	0.89[a]	0.83[a]
S1	SF	1.90[a]	1.29[a]	1.17[a]	1.05[a]	0.97[a]
S2	SW	2.35[a]	1.73[a]	1.46[a]	1.23[a]	1.14[a]
S3	CC	2.44[a]	1.68[a]	1.22[a]	0.90[a]	0.76[a]
S4	CR	2.49[a]	1.70[a]	1.58[a]	1.36[a]	1.02[a]
S5	PB	2.14[a]	1.48[a]	1.15[a]	0.92[a]	0.89[a]
Grazing (G)						
Yes		2.26[a]	1.63[a]	1.32[a]	1.03[a]	0.88[a]
No		2.30[a]	1.55[a]	1.29[a]	1.07[a]	0.94[a]
		Analysis of variance *P>F*				
S		0.62	0.82	0.5	0.22	0.44
G		0.47	0.92	0.99	0.71	0.81
S×G		0.92	0.99	0.96	0.87	0.98

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.11. Means of wet soil aggregate stability (WAS) as influenced by different cropping sequences for the 0-5 and 5-15 cm depths in 2016.

Treatments		2016 Soil Depths (cm)	
Sequence (S) [§]	*Crop*	0-5	5-15
		----Wet Aggregate Stability (%)---	
CNT	SW	88.3[a†]	88.5[a]
S1	PB	88.6[a]	84.9[a]
S2	SF	97.2[a]	87.6[a]
S3	SW	87.5[a]	90.2[a]
S4	CC	89.3[a]	93.7[a]
S5	CR	90.3[a]	93.0[a]
		Analysis of variance *P>F*	
S		0.11	0.73

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.12. Means of wet soil aggregate stability (WAS) as influenced by different cropping sequences and grazing treatments for the 0-5 and 5-15 cm depths in 2017.

Treatments		2017 Soil Depths (cm)	
Sequence (S) [§]	*Crop*	0-5	5-15
		---Wet Aggregate Stability (%)---	
CNT	SW	85.2[a]	89.6[a]
S1	SF	85.7[a]	95.9[a]
S2	SW	96.4[a]	88.3[a]
S3	CC	96.2[a]	94.1[a]
S4	CR	96.5[a]	93.0[a]
S5	PB	92.4[a]	90.4[a]
Grazing (G)			
Yes		96.1[a]	92.1[a]
No		91.7[a]	92.1[a]
		Analysis of variance P>F	
S		0.29	0.16
G		0.8	0.67
S×G		0.47	0.88

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.13. Means of soil carbon fractions as influenced by different cropping sequences for the 0-5 cm depth in 2016.

Treatments		2016 Soil Depth (cm) 0-5			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Carbon Fractions (µg g^{-1})			
CNT	SW	26.6[a†]	72.2[a]	195.9[a]	72.3[a]
S1	PB	27.3[a]	72.8[a]	289.0[a]	100.0[a]
S2	SF	24.1[a]	83.7[a]	261.6[a]	99.0[a]
S3	SW	25.9[a]	85.2[a]	355.0[a]	122.0[a]
S4	CC	21.4[a]	70.8[a]	240.5[a]	76.7[a]
S5	CR	26.0[a]	81.6[a]	445.4[a]	139.2[a]
		Analysis of variance *P>F*			
S		0.83	0.96	0.53	0.45

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.14. Means of soil carbon fractions as influenced by different cropping sequences for the 5-15 cm depth in 2016.

Treatments		2016 Soil Depth (cm) 5-15			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Carbon fractions (µg g^{-1})			
CNT	SW	20.4[a†]	54.6[a]	220.6[a]	73.9[a]
S1	PB	14.0[b]	33.5[a]	297.9[a]	74.1[a]
S2	SF	15.2[b]	42.8[a]	136.9[a]	45.9[a]
S3	SW	15.9[b]	40.4[a]	150.1[a]	64.7[a]
S4	CC	14.7[b]	43.5[a]	143.0[a]	60.0[a]
S5	CR	15.4[b]	36.7[a]	192.8[a]	65.6[a]
		Analysis of variance *P>F*			
S		0.05	0.15	0.61	0.96

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.15. Means of soil carbon fractions as influenced by different cropping sequences and grazing treatments for the 0-5 cm depth in 2017.

Treatments		2017 Soil Depth (cm) 0-5			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Carbon Fractions (µg g^{-1})			
CNT	SW	29.0[a†]	69.8[a]	376.9[a]	215.1[a]
S1	SF	28.0[a]	69.1[a]	190.9[a]	172.0[a]
S2	SW	33.3[a]	69.7[a]	237.4[a]	184.9[a]
S3	CC	30.1[a]	84.4[a]	246.9 [a]	245.1[a]
S4	CR	28.5[a]	82.6[a]	248.7[a]	220.9[a]
S5	PB	28.6[a]	67.4[a]	303.1[a]	214.4[a]
Grazing (G)					
Yes		28.5[a]	73.3[a]	227.6[a]	221.0[a]
No		29.9[a]	76.2[a]	286.6[a]	211.6[a]
		Analysis of variance *P>F*			
S		0.92	0.56	0.21	0.16
G		0.71	0.36	0.11	0.54
S × G		0.87	0.87	0.9	0.09

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.16. Means of soil carbon fractions as influenced by different cropping sequences and grazing treatments for the 5-15 cm depth in 2017.

Treatments		2017 Soil Depth (cm) 5-15			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Carbon Fractions (µg g^{-1})			
CNT	SW	19.4[a†]	34.9[a]	188.4[a]	140.3[a]
S1	SF	19.3[a]	34.5[a]	149.9[a]	117.6[a]
S2	SW	19.5[a]	36.9[a]	155.5[a]	126.8[a]
S3	CC	22.7[a]	44.0[a]	163.3[a]	165.5[a]
S4	CR	19.8[a]	39.6[a]	142.7[a]	144.5[a]
S5	PB	18.8[a]	33.7[a]	187.6[a]	152.5[a]
Grazing (G)					
Yes		19.9[a]	39.2[a]	165.9[a]	156.2[a]
No		20.2[a]	37.2[a]	163.9 [a]	140.2[a]
		Analysis of variance *P>F*			
S		0.54	0.54	0.78	0.39
G		0.55	0.97	0.92	0.76
S × G		0.96	0.81	0.81	0.56

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.17. Means of soil nitrogen fractions as influenced by different cropping sequences for the 0-5 cm depth in 2016.

Treatments		2016 Soil Depth (cm) 0-5			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Nitrogen Fractions (µg g^{-1})			
CNT	SW	3.10[a†]	7.85[a]	35.3[a]	12.9[a]
S1	PB	2.81[a]	8.18[a]	43.1[a]	20.0[a]
S2	SF	3.37[a]	8.85[a]	39.5[a]	18.6[a]
S3	SW	3.20[a]	9.00[a]	52.6[a]	21.1[a]
S4	CC	3.15[a]	7.46[a]	36.0[a]	14.9[a]
S5	CR	4.34[a]	8.37[a]	65.3[a]	26.5[a]
		Analysis of variance *P>F*			
S		0.78	0.99	0.69	0.39

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.18. Means of soil nitrogen fractions as influenced by different cropping sequences for the 5-15 cm depth in 2016.

Treatments		2016 Soil Depth (cm) 5-15			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Nitrogen Fractions (µg g^{-1})			
CNT	SW	2.17[a†]	5.51[a]	33.0[a]	14.3[a]
S1	PB	1.94[a]	3.80[a]	41.3[a]	14.7[a]
S2	SF	1.77[a]	4.23[a]	19.4[a]	8.70[a]
S3	SW	1.58[a]	4.14[a]	20.5[a]	12.5[a]
S4	CC	2.21[a]	4.16[a]	19.9[a]	11.7[a]
S5	CR	2.44[a]	3.71[a]	28.0[a]	13.5[a]
		Analysis of variance *P>F*			
S		0.5	0.71	0.62	0.95

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.19. Means of soil nitrogen fractions as influenced by different cropping sequences and grazing treatments for the 0-5 cm depth in 2017.

Treatments		2017 Soil Depth (cm) 0-5			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Nitrogen Fractions (µg g^{-1})			
CNT	SW	1.51[a†]	2.88[a]	28.0[a]	26.0[a]
S1	SF	1.52[a]	3.07[a]	15.8[a]	19.1[a]
S2	SW	1.70[a]	2.54[a]	13.6[a]	20.0[a]
S3	CC	2.19[a]	3.83[a]	23.4[a]	19.7[a]
S4	CR	1.65[a]	3.14[a]	20.5[a]	20.6[a]
S5	PB	1.88[a]	3.08[a]	22.6[a]	23.2[a]
Grazing (G)					
Yes		1.98[a]	3.12[a]	18.9[b]	20.0[a]
No		1.71[a]	3.21[a]	22.3[a]	22.0[a]
		Analysis of variance *P>F*			
S		0.77	0.59	0.16	0.62
G		0.68	0.41	0.09	0.42
S × G		0.47	0.98	0.77	0.49

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.20. Means of soil nitrogen fractions as influenced by different cropping sequences and grazing treatments for the 5-15 cm depth in 2017.

Treatments		2017 Soil Depth (cm) 5-15			
Sequence (S) [§]	*Crop*	Labile	Stable	Inert (1M)	Inert (6M)
		Nitrogen Fractions (µg g^{-1})			
CNT	SW	0.95[a†]	1.34[a]	14.8[a]	16.7[a]
S1	SF	0.76[a]	1.45[a]	12.7[a]	15.2[a]
S2	SW	1.01[a]	1.42[a]	12.7[a]	13.6[a]
S3	CC	1.04[a]	1.90[a]	14.9[a]	13.6[a]
S4	CR	0.98[a]	1.46[a]	12.1[a]	15.1[a]
S5	PB	0.96[a]	1.41[a]	13.7[a]	17.0[a]
Grazing (G)					
Yes		0.99[a]	1.59[a]	13.9[a]	14.6[a]
No		0.95[a]	1.50[a]	13.4[a]	15.5[a]
		Analysis of variance *P>F*			
S		0.75	0.47	0.95	0.43
G		0.99	0.96	0.83	0.42
S × G		0.83	0.82	0.93	0.53

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.21. Means of soil microbial biomass carbon (MBC) as influenced by different cropping sequences for the 0-5 cm depth in 2016.

Treatments		2016 MBC
Sequence (S) [§]	*Crop*	(mg kg^{-1})
CNT	SW	347.6[a†]
S1	PB	335.8[a]
S2	SF	439.3[a]
S3	SW	573.5[a]
S4	CC	471.3[a]
S5	CR	306.0[a]
	Analysis of variance *P>F*	
S		0.35

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.22. Means of soil microbial biomass carbon (MBC) and soil microbial biomass nitrogen (MBN) as influenced by different cropping sequences and grazing treatments for the 0-5 cm depth in 2017.

Treatments		2017	
		MBC	MBN
Sequence (S) [§]	*Crop*	(mg kg^{-1})	
CNT	SW	282.4[a]	6.90[a]
S1	SF	518.9[a]	24.4[a]
S2	SW	507.3[a]	17.0[a]
S3	CC	431.8[a]	25.2[a]
S4	CR	443.3[a]	20.3[a]
S5	PB	428.8[a]	14.0[a]
Grazing(G)			
Yes		426.1[a]	20.9[a]
No		439.7[a]	19.0[a]
		Analysis of variance *P>F*	
S		0.77	0.88
G		0.76	0.96
S×G		0.88	0.89

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.23. Means of soil urease and beta-glucosidase activities as influenced by different cropping sequences for the 0-5 cm depth in 2016.

Treatments		2016	
		Urease	Beta-glucosidase
Sequence (S) [§]	*Crop*	(µg g^{-1} h^{-1})	(µg g^{-1} h^{-1})
CNT	SW	149.3[a†]	27.2[a]
S1	PB	146.6[a]	42.6[a]
S2	SF	144.1[a]	64.4[a]
S3	SW	134.1[a]	91.7[a]
S4	CC	160.4[a]	53.7[a]
S5	CR	144.3[a]	23.5[a]
		Analysis of variance *P>F*	
S		0.91	0.31

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.24. Means of soil urease and beta-glucosidase activities as influenced by different cropping sequences and grazing treatments for the 0-5 cm depth in 2017.

Treatments		2017	
		Urease	Beta-glucosidase
Sequence (S) [§]	*Crop*	(µg g^{-1} h^{-1})	(µg g^{-1} h^{-1})
CNT	SW	161.5[a]	105.3[a]
S1	SF	234.6[a]	167.0[a]
S2	SW	254.8[a]	199.7[a]
S3	CC	252.2[a]	227.3[a]
S4	CR	268.3[a]	294.0[a]
S5	PB	195.0[a]	218.9[a]
Grazing(G)			
Yes		234.0[a]	236.3[a]
No		255.0[a]	207.3[a]
		Analysis of variance *P>F*	
S		0.73	0.48
G		0.9	0.74
S×G		0.83	0.95

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.
Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.
[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.25. Means of soil water retention as influenced by different cropping sequences for the 0-5 cm depth in 2016.

Treatments		2016						
		Soil Water Pressure (-kPa)						
Sequence (S) [§]	*Crop*	0.01	0.4	1.0	2.5	5.0	10	30
		Soil Water Content (m^3 m^{-3})						
CNT	SW	0.563[a†]	0.557[a]	0.554[a]	0.547[a]	0.539[a]	0.473[a]	0.437[a]
S1	PB	0.568[a]	0.565[a]	0.561[a]	0.556[a]	0.547[a]	0.464[a]	0.426[a]
S2	SF	0.588[a]	0.583[a]	0.578[a]	0.569[a]	0.557[a]	0.498[a]	0.458[a]
S3	SW	0.594[a]	0.589[a]	0.583[a]	0.574[a]	0.563[a]	0.480[a]	0.437[a]
S4	CC	0.543[a]	0.537[a]	0.532[a]	0.525[a]	0.515[a]	0.455[a]	0.411[a]
S5	CR	0.517[a]	0.513[a]	0.506[a]	0.498[a]	0.486[a]	0.406[a]	0.348[a]
		Analysis of variance $P>F$						
S		0.83	0.84	0.84	0.86	0.87	0.87	0.7

[§]CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

Crop: Previous Crop; SW: Spring Wheat; PB: Pea/Barely; SF: Sunflower; CC: Cover Crop; CR: Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

Table 4.26. Means of soil water retention as influenced by different cropping sequences and grazing treatments for the 0-5 cm depth in 2017.

Treatments		2017 Soil Water Pressure (-kPa)						
Sequence (S) [§]	*Crop*	0.01	0.4	1.0	2.5	5.0	10	30
		Soil Water Content (m^3 m^{-3})						
CNT	SW	0.550[a†]	0.545[a]	0.543[a]	0.539[a]	0.535[a]	0.408[a]	0.381[a]
S1	SF	0.547[a]	0.542[a]	0.538[a]	0.534[a]	0.531[a]	0.383[a]	0.360[a]
S2	SW	0.562[a]	0.556[a]	0.552[a]	0.549[a]	0.543[a]	0.394[a]	0.376[a]
S3	CC	0.541[a]	0.536[a]	0.522[a]	0.528[a]	0.524[a]	0.400[a]	0.375[a]
S4	CR	0.558[a]	0.552[a]	0.548[a]	0.543[a]	0.540[a]	0.396[a]	0.371[a]
S5	PB	0.559[a]	0.551[a]	0.545[a]	0.541[a]	0.535[a]	0.381[a]	0.351[a]
Grazing (G)								
Yes		0.554[a]	0.547[a]	0.543[a]	0.538[a]	0.534[a]	0.388[a]	0.361[a]
No		0.551[a]	0.546[a]	0.539[a]	0.538[a]	0.534[a]	0.396[a]	0.371[a]
		Analysis of variance $P>F$						
S		0.93	0.95	0.8	0.96	0.96	0.82	0.81
G		0.88	0.93	0.66	0.97	0.99	0.53	0.55
S × G		0.52	0.6	0.65	0.63	0.64	0.67	0.64

S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

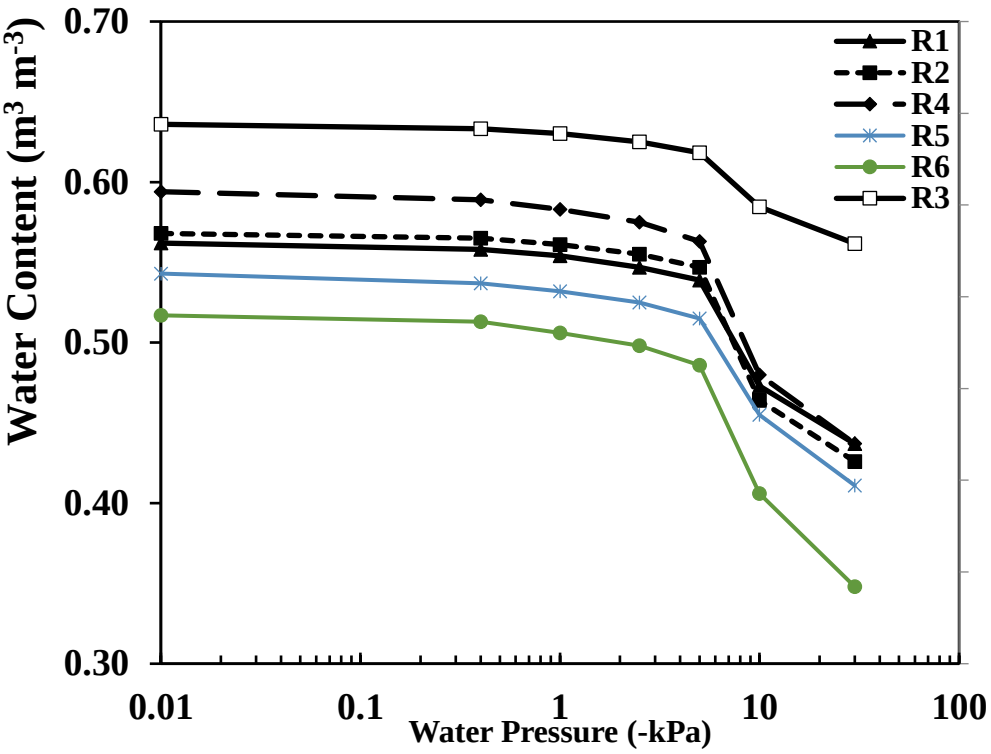

Figure 4.1. Soil water retention (m^3 m^{-3}) as influenced by ICLS practice for 0- to 5- cm depth in 2016. Note: CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

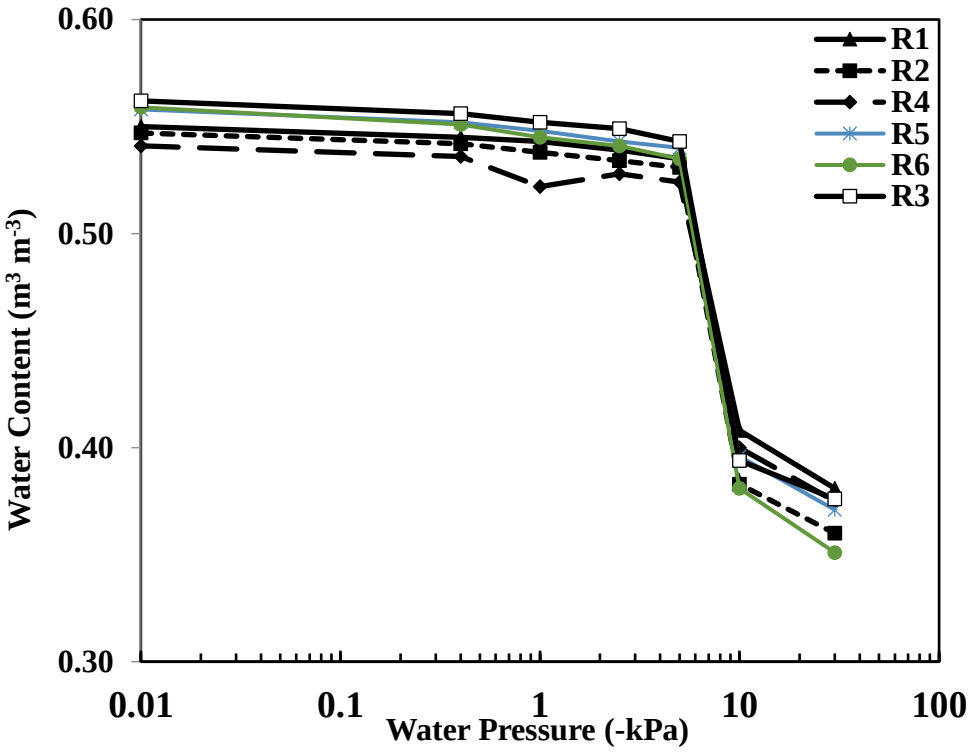

Figure 4.2. Soil water retention (m^3 m^{-3}) as influenced by ICLS practice for 0- to 5- cm depth in 2017. Note: CNT: Continuous Spring Wheat (Control). S1: Sunflower (*Helianthus annuus* L.)-Spring Wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring Wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring Wheat. S4: Corn-Pea/Barely-Sunflower-Spring Wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring Wheat-Cover Crop-Corn.

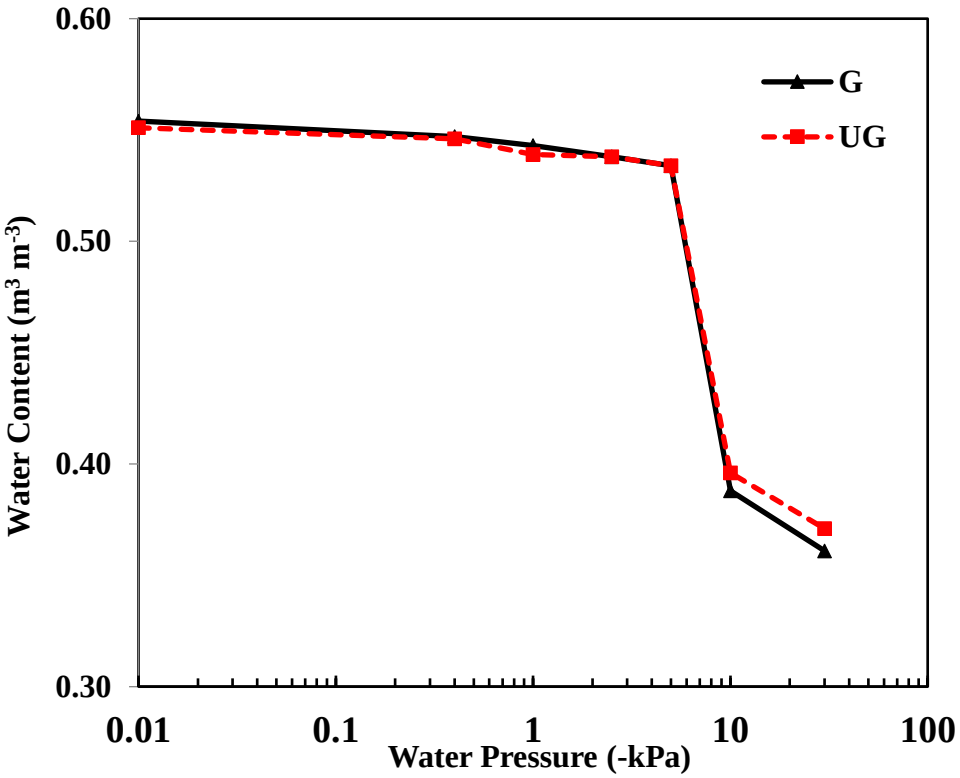

Figure 4.3. Soil water retention (m^3 m^{-3}) as influenced by grazing treatment under ICLS practice for 0- to 5- cm depth in 2017. Note: G: Grazed and UG: Un-grazed.

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CHAPTER 5

CONCLUSIONS

This study was conducted to explore the response of crop diversity and livestock grazing practice under ICLS to soil properties in Dickinson, North Dakota. Soil properties were compared between five cropping sequences and the continuous spring wheat, and between grazed and un-grazed. The conclusions of this study are mentioned below as:

1. Data showed that cropping sequences treatments (averaged across all the depths) significantly influenced soil organic carbon (SOC). Averaged across 0- to 60- cm depth, the mean soil organic carbon content of cropping sequence 3 (S3) (23.1 g kg^{-1}) (cover crop-corn-pea/barely-sunflower-spring wheat) had significantly higher value than the continuous spring wheat treatment (16.4 g kg^{-1}) in 2016. However, no significant differences in each depth. Grazing did not have significant negative influence on SOC.
2. The average of soil bulk density (BD) over 0- to 60-cm depth for cropping sequence 3 (S3) treatment (1.19 Mg m^{-3}) were significantly lower than all the other treatments in 2016, especially the continuous spring wheat treatment (1.32 Mg m^{-3}), it may due to the higher soil organic carbon reduced the bulk density. The soil BD mean values response to cropping sequences treatment were non-significant in each depth. Grazing treatment significantly lower the soil BD value only at 0- to 5- cm depth in 2017.
3. Soil water content in cropping sequence 3 (S3) (Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat) had numerically marginally higher water content as

compared with other treatments in 2016, although not statistically significant. Grazing did not affect the soil water content at 0- to 5- cm depth in 2017.

4. Soil cropping sequences and grazing treatment did not significant impact the soil microbial biomass carbon, soil microbial biomass nitrogen, urease enzyme activity, beta-glucosidase enzymes activity (for 0- to 5- cm), soil aggregate stability, soil labile, stable, and inert carbon, soil labile, stable, and inert nitrogen fractions (for 5- to 15- cm) total nitrogen (at 0- to 60- cm).

This study demonstrated the effects that influenced by diverse cropping sequences and grazing treatments under ICLS on soil properties. The results from this study showed that cropping sequences treatment under ICLS had the ability to maintain or improve the soil organic carbon concentration. The grazing treatment under ICLS had slightly higher soil bulk density at the shallow depth may due to moisture changes and the livestock traffic, but can be alleviate by using the diverse cropping sequences as various of crop residues or organic matter inputs. Soil bulk density can be influenced by other factors such as residue on the surface, organic carbon, therefore, using the diverse cropping sequences under ICLS can reduce the soil compaction problem created by the grazing cattle. Future study needed to characterize the long-term grazing and cropping sequences impact on the soil quality.

APPENDICES

APPENDIX 1

A1.1 Soil bulk density (Mg m^{-3}) for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths in 2016. TRT, treatment; REP, replication; BD, bulk density.

Plot ID	TRT	REP	Depth (cm)	BD (Mg m^{-3})
1916	CNT	1	0-5	0.87
1916	CNT	1	5-15	1.39
1916	CNT	1	15-30	1.31
1916	CNT	1	30-45	1.40
1916	CNT	1	45-60	1.36
1922	CNT	2	0-5	1.44
1922	CNT	2	5-15	1.31
1922	CNT	2	15-30	1.37
1922	CNT	2	30-45	1.29
1922	CNT	2	45-60	1.28
1928	CNT	3	0-5	1.43
1928	CNT	3	5-15	1.23
1928	CNT	3	15-30	1.30
1928	CNT	3	30-45	1.45
1928	CNT	3	45-60	1.41
1917	S1	1	0-5	1.21
1917	S1	1	5-15	1.22
1917	S1	1	15-30	1.27
1917	S1	1	30-45	1.39
1917	S1	1	45-60	1.34
1921	S1	2	0-5	1.54
1921	S1	2	5-15	1.47
1921	S1	2	15-30	1.41
1921	S1	2	30-45	1.29
1921	S1	2	45-60	1.34
1924	S1	3	0-5	1.29
1924	S1	3	5-15	1.39
1924	S1	3	15-30	1.30
1924	S1	3	30-45	1.14
1924	S1	3	45-60	1.51
1913	S2	2	0-5	1.17
1913	S2	2	5-15	1.32
1913	S2	2	15-30	1.36
1913	S2	2	30-45	1.39
1913	S2	2	45-60	1.38
1918	S2	1	0-5	1.11

A1.1 Cont'd

Plot ID	TRT	REP	Depth (cm)	BD (Mg m^{-3})
1918	S2	1	5-15	1.36
1918	S2	1	15-30	1.32
1918	S2	1	30-45	1.25
1918	S2	1	45-60	1.33
1926	S2	3	0-5	1.26
1926	S2	3	5-15	1.48
1926	S2	3	15-30	1.38
1926	S2	3	30-45	1.37
1926	S2	3	45-60	1.30
1915	S3	1	0-5	0.99
1915	S3	1	5-15	1.28
1915	S3	1	15-30	1.25
1915	S3	1	30-45	1.20
1915	S3	1	45-60	1.25
1920	S3	2	0-5	1.13
1920	S3	2	5-15	1.23
1920	S3	2	15-30	1.05
1920	S3	2	30-45	1.07
1920	S3	2	45-60	1.19
1930	S3	3	0-5	1.19
1930	S3	3	5-15	1.28
1930	S3	3	15-30	1.27
1930	S3	3	30-45	1.27
1930	S3	3	45-60	1.25
1919	S4	1	0-5	1.24
1919	S4	1	5-15	1.30
1919	S4	1	15-30	1.33
1919	S4	1	30-45	1.32
1919	S4	1	45-60	1.31
1927	S4	2	0-5	1.11
1927	S4	2	5-15	1.36
1927	S4	2	15-30	1.34
1927	S4	2	30-45	1.51
1927	S4	2	45-60	1.40
1929	S4	3	0-5	1.15
1929	S4	3	5-15	1.20
1929	S4	3	15-30	1.13
1929	S4	3	30-45	1.28

A1.1 Cont'd

Plot ID	TRT	REP	Depth (cm)	BD (Mg m^{-3})
1929	S4	3	45-60	1.43
1914	S5	1	0-5	1.02
1914	S5	1	5-15	1.12
1914	S5	1	15-30	1.35
1914	S5	1	30-45	1.32
1914	S5	1	45-60	1.38
1923	S5	2	0-5	1.29
1923	S5	2	5-15	1.42
1923	S5	2	15-30	1.37
1923	S5	2	30-45	1.26
1923	S5	2	45-60	1.29
1925	S5	3	0-5	0.90
1925	S5	3	5-15	1.43
1925	S5	3	15-30	1.39
1925	S5	3	30-45	1.26
1925	S5	3	45-60	1.02

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.2 Soil pH and electrical conductivity (dS m^{-1}) for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths in 2016. TRT, treatment; REP, replication; EC, electrical conductivity.

Plot ID	TRT	REP	Depth (cm)	pH	EC (dS m^{-1})
1916	CNT	1	0-5	5.42	0.214
1916	CNT	1	5-15	5.05	0.114
1916	CNT	1	15-30	6.19	0.132
1916	CNT	1	30-45	6.59	0.129
1916	CNT	1	45-60	7.80	0.262
1922	CNT	2	0-5	4.60	0.113
1922	CNT	2	5-15	4.53	0.072
1922	CNT	2	15-30	5.95	0.214
1922	CNT	2	30-45	6.53	0.219
1922	CNT	2	45-60	7.72	0.268
1928	CNT	3	0-5	6.34	0.188
1928	CNT	3	5-15	6.82	0.249
1928	CNT	3	15-30	7.44	0.178
1928	CNT	3	30-45	7.66	0.144
1928	CNT	3	45-60	7.67	0.141
1917	S1	1	0-5	6.49	0.239
1917	S1	1	5-15	5.69	0.120
1917	S1	1	15-30	5.92	0.112
1917	S1	1	30-45	6.51	0.148
1917	S1	1	45-60	7.56	0.246
1921	S1	2	0-5	5.09	0.146
1921	S1	2	5-15	5.14	0.088
1921	S1	2	15-30	6.34	0.176
1921	S1	2	30-45	7.37	0.302
1921	S1	2	45-60	7.86	0.245
1924	S1	3	0-5	6.05	0.206
1924	S1	3	5-15	5.48	0.110
1924	S1	3	15-30	7.22	0.242
1924	S1	3	30-45	7.58	0.209
1924	S1	3	45-60	7.91	0.176
1913	S2	2	0-5	6.31	0.352
1913	S2	2	5-15	5.27	0.105
1913	S2	2	15-30	6.25	0.183
1913	S2	2	30-45	6.31	0.352
1913	S2	2	45-60	8.03	0.218
1918	S2	1	0-5	5.58	0.163
1918	S2	1	5-15	4.74	0.087
1918	S2	1	15-30	5.45	0.094

A1.2 Cont'd

Plot ID	TRT	REP	Depth (cm)	pH	EC (dS m^{-1})
1918	S2	1	30-45	5.42	0.108
1918	S2	1	45-60	5.55	0.092
1926	S2	3	0-5	4.64	0.102
1926	S2	3	5-15	4.94	0.058
1926	S2	3	15-30	5.92	0.079
1926	S2	3	30-45	6.49	0.089
1926	S2	3	45-60	7.74	0.234
1915	S3	1	0-5	5.73	0.191
1915	S3	1	5-15	4.95	0.085
1915	S3	1	15-30	6.31	0.150
1915	S3	1	30-45	7.35	0.325
1915	S3	1	45-60	7.88	0.217
1920	S3	2	0-5	5.47	0.128
1920	S3	2	5-15	5.06	0.085
1920	S3	2	15-30	6.08	0.077
1920	S3	2	30-45	6.89	0.236
1920	S3	2	45-60	7.67	0.208
1930	S3	3	0-5	7.67	0.160
1930	S3	3	5-15	7.85	0.142
1930	S3	3	15-30	7.94	0.142
1930	S3	3	30-45	8.07	0.139
1930	S3	3	45-60	8.08	0.119
1919	S4	1	0-5	5.02	0.142
1919	S4	1	5-15	4.79	0.086
1919	S4	1	15-30	5.95	0.093
1919	S4	1	30-45	7.56	0.242
1919	S4	1	45-60	7.90	0.210
1927	S4	2	0-5	6.45	0.143
1927	S4	2	5-15	6.92	0.162
1927	S4	2	15-30	7.61	0.182
1927	S4	2	30-45	7.85	0.163
1927	S4	2	45-60	7.96	0.158
1929	S4	3	0-5	5.56	0.178
1929	S4	3	5-15	4.97	0.146
1929	S4	3	15-30	5.46	0.120
1929	S4	3	30-45	5.75	0.106
1929	S4	3	45-60	5.82	0.077
1914	S5	1	0-5	5.92	0.297
1914	S5	1	5-15	5.02	0.117

A1.2 Cont'd

Plot ID	TRT	REP	Depth (cm)	pH	EC (dS m^{-1})
1914	S5	1	15-30	6.00	0.135
1914	S5	1	30-45	6.92	0.260
1914	S5	1	45-60	7.97	0.234
1923	S5	2	0-5	5.86	0.190
1923	S5	2	5-15	4.71	0.133
1923	S5	2	15-30	5.69	0.112
1923	S5	2	30-45	7.16	0.250
1923	S5	2	45-60	7.54	0.237
1925	S5	3	0-5	6.57	0.283
1925	S5	3	5-15	5.99	0.149
1925	S5	3	15-30	5.90	0.119
1925	S5	3	30-45	6.55	0.181
1925	S5	3	45-60	7.24	0.289

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.3 Soil organic carbon (g kg^{-1}) and total nitrogen (g kg^{-1}) for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths in 2016. TRT, treatment; REP, replication; SOC, soil organic carbon; TN, total nitrogen.

Plot ID	TRT	REP	Depth (cm)	SOC (g kg^{-1})	TN (g kg^{-1})
1916	CNT	1	0-5	33.10	2.70
1916	CNT	1	5-15	20.19	1.79
1916	CNT	1	15-30	15.96	1.33
1916	CNT	1	30-45	10.79	1.17
1916	CNT	1	45-60	16.20	1.06
1922	CNT	2	0-5	24.04	2.26
1922	CNT	2	5-15	17.67	1.64
1922	CNT	2	15-30	13.11	1.20
1922	CNT	2	30-45	11.78	0.93
1922	CNT	2	45-60	16.84	0.88
1928	CNT	3	0-5	12.36	1.24
1928	CNT	3	5-15	12.76	0.76
1928	CNT	3	15-30	16.77	0.54
1928	CNT	3	30-45	16.27	0.48
1928	CNT	3	45-60	7.76	0.37
1917	S1	1	0-5	28.22	2.13
1917	S1	1	5-15	25.05	1.93
1917	S1	1	15-30	15.06	1.47
1917	S1	1	30-45	11.66	1.23
1917	S1	1	45-60	15.29	0.96
1921	S1	2	0-5	24.57	2.10
1921	S1	2	5-15	14.10	1.23
1921	S1	2	15-30	13.27	0.97
1921	S1	2	30-45	21.89	1.25
1921	S1	2	45-60	23.17	0.99
1924	S1	3	0-5	21.93	1.83
1924	S1	3	5-15	16.22	1.46
1924	S1	3	15-30	16.80	1.33
1924	S1	3	30-45	30.31	1.06
1924	S1	3	45-60	32.92	0.75
1913	S2	2	0-5	32.06	2.67
1913	S2	2	5-15	21.09	1.90
1913	S2	2	15-30	20.66	1.59
1913	S2	2	30-45	20.05	1.74
1913	S2	2	45-60	12.50	1.08
1918	S2	1	0-5	24.33	1.93
1918	S2	1	5-15	17.87	1.78

A1.3 Cont'd

Plot ID	TRT	REP	Depth (cm)	SOC (g kg^{-1})	TN (g kg^{-1})
1918	S2	1	15-30	12.65	1.23
1918	S2	1	30-45	14.31	1.18
1918	S2	1	45-60	23.08	0.99
1926	S2	3	0-5	23.63	1.95
1926	S2	3	5-15	14.87	1.29
1926	S2	3	15-30	12.43	1.23
1926	S2	3	30-45	13.96	1.14
1926	S2	3	45-60	19.25	0.92
1915	S3	1	0-5	32.65	2.75
1915	S3	1	5-15	19.25	1.78
1915	S3	1	15-30	15.13	1.41
1915	S3	1	30-45	14.27	1.32
1915	S3	1	45-60	21.27	1.11
1920	S3	2	0-5	28.65	2.32
1920	S3	2	5-15	20.60	1.78
1920	S3	2	15-30	15.11	1.41
1920	S3	2	30-45	11.48	1.17
1920	S3	2	45-60	19.31	1.15
1930	S3	3	0-5	35.09	1.43
1930	S3	3	5-15	30.34	1.10
1930	S3	3	15-30	36.14	0.83
1930	S3	3	30-45	39.69	0.48
1930	S3	3	45-60	7.37	0.34
1919	S4	1	0-5	26.71	2.30
1919	S4	1	5-15	17.73	1.52
1919	S4	1	15-30	11.95	1.30
1919	S4	1	30-45	16.84	1.09
1919	S4	1	45-60	21.53	0.94
1927	S4	2	0-5	13.50	1.41
1927	S4	2	5-15	10.50	1.06
1927	S4	2	15-30	15.42	0.80
1927	S4	2	30-45	12.36	0.77
1927	S4	2	45-60	17.91	0.56
1929	S4	3	0-5	36.71	2.84
1929	S4	3	5-15	25.65	1.85
1929	S4	3	15-30	25.46	1.87
1929	S4	3	30-45	24.59	1.76
1929	S4	3	45-60	14.14	1.19
1914	S5	1	0-5	38.05	3.05

A1.3 Cont'd

Plot ID	TRT	REP	Depth (cm)	SOC (g kg^{-1})	TN (g kg^{-1})
1914	S5	1	5-15	19.42	1.81
1914	S5	1	15-30	14.81	1.46
1914	S5	1	30-45	11.03	1.24
1914	S5	1	45-60	17.10	0.98
1923	S5	2	0-5	21.51	1.98
1923	S5	2	5-15	13.23	1.26
1923	S5	2	15-30	9.14	0.88
1923	S5	2	30-45	8.47	0.85
1923	S5	2	45-60	8.97	0.84
1925	S5	3	0-5	15.80	1.42
1925	S5	3	5-15	14.07	1.15
1925	S5	3	15-30	9.44	0.87
1925	S5	3	30-45	9.87	0.99
1925	S5	3	45-60	10.16	0.93

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.4 Wet soil aggregate stability (%) for 0-5, and 5-15 cm depths in 2016. TRT, treatment; REP, replication; WAS, wet soil aggregate stability.

Plot ID	TRT	REP	Depth (cm)	WAS (%)
1916	CNT	1	0-5	94.1
1916	CNT	1	5-15	90.9
1922	CNT	2	0-5	81.8
1922	CNT	2	5-15	88.1
1928	CNT	3	0-5	89.1
1928	CNT	3	5-15	86.3
1917	S1	1	0-5	97.9
1917	S1	1	5-15	99.7
1921	S1	2	0-5	76.4
1921	S1	2	5-15	74.4
1924	S1	3	0-5	91.6
1924	S1	3	5-15	80.7
1913	S2	1	0-5	97.5
1913	S2	1	5-15	92.2
1918	S2	2	0-5	94.9
1918	S2	2	5-15	91.7
1926	S2	3	0-5	99.3
1926	S2	3	5-15	78.8
1915	S3	1	0-5	89.0
1915	S3	1	5-15	88.8
1920	S3	2	0-5	81.6
1920	S3	2	5-15	99.7
1930	S3	3	0-5	91.9
1930	S3	3	5-15	82.0
1919	S4	1	0-5	88.6
1919	S4	1	5-15	96.0
1927	S4	2	0-5	85.2
1927	S4	2	5-15	91.0
1929	S4	3	0-5	94.1
1929	S4	3	5-15	94.0
1914	S5	1	0-5	92.9
1914	S5	1	5-15	92.7
1923	S5	2	0-5	87.9
1923	S5	2	5-15	86.6
1925	S5	3	0-5	90.1
1925	S5	3	5-15	99.7

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.5 Soil water retention (m^3 m^{-3}) for 0-5 cm depth in 2016. TRT, treatment; REP, replication;

Plot ID	TRT	REP	0 (-kPa)	0.4 (-kPa)	1 (-kPa)	2.5 (-kPa)	5 (-kPa)	10 (-kPa)	30 (-kPa)
1916	CNT	1	0.658	0.654	0.651	0.646	0.636	0.570	0.535
1922	CNT	2	0.601	0.598	0.594	0.585	0.575	0.508	0.484
1928	CNT	3	0.429	0.420	0.416	0.410	0.405	0.342	0.292
1917	S1	1	0.623	0.620	0.616	0.610	0.602	0.510	0.479
1921	S1	2	0.518	0.515	0.511	0.504	0.496	0.428	0.399
1924	S1	3	0.563	0.560	0.557	0.553	0.543	0.455	0.400
1913	S2	1	0.605	0.602	0.599	0.593	0.577	0.504	0.485
1918	S2	2	0.672	0.669	0.665	0.660	0.654	0.597	0.540
1926	S2	3	0.487	0.479	0.470	0.454	0.440	0.394	0.349
1915	S3	1	0.619	0.616	0.612	0.607	0.595	0.492	0.465
1920	S3	2	0.683	0.677	0.672	0.665	0.655	0.576	0.526
1930	S3	3	0.481	0.473	0.466	0.451	0.438	0.373	0.320
1919	S4	1	0.602	0.599	0.594	0.588	0.580	0.521	0.481
1927	S4	2	0.434	0.426	0.417	0.407	0.392	0.308	0.273
1929	S4	3	0.594	0.587	0.584	0.579	0.574	0.535	0.480
1914	S5	1	0.598	0.597	0.593	0.588	0.577	0.505	0.436
1923	S5	2	0.505	0.503	0.500	0.495	0.488	0.410	0.348
1925	S5	3	0.449	0.438	0.426	0.410	0.392	0.303	0.261

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.6 Soil beta-glucosidase enzymes (µg g^{-1} h^{-1}), urease enzymes (µg g^{-1} h^{-1}), and microbial biomass carbon (mg kg^{-1}) for 0-5 cm depth in 2016. TRT, treatment; REP, replication; MBC, microbial biomass carbon.

Plot ID	TRT	REP	Beta-glucosidase (µg g^{-1} h^{-1})	Urease (µg g^{-1} h^{-1})	MBC (mg kg^{-1})
1916	CNT	1	39.1	171.8	390.0
1922	CNT	2	24.6	154.1	439.2
1928	CNT	3	17.8	122.0	213.5
1917	S1	1	47.8	143.4	305.2
1921	S1	2	29.2	165.0	314.5
1924	S1	3	50.8	131.7	387.7
1913	S2	2	90.5	117.6	381.1
1918	S2	1	86.1	165.7	471.3
1926	S2	3	16.5	148.9	465.6
1915	S3	1	34.2	175.3	833.5
1920	S3	2	108.9	150.0	193.2
1930	S3	3	131.8	76.9	693.8
1919	S4	1	26.0	152.6	568.7
1927	S4	2	13.4	141.4	483.1
1929	S4	3	121.8	187.1	362.0
1914	S5	1	36.1	162.1	372.6
1923	S5	2	30.6	134.4	317.4
1925	S5	3		136.4	228.0

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.7 Soil carbon fraction (μg g^{-1}) for 0-5 and 5-15 cm depths in 2016. TRT, treatment; REP, replication.

Plot ID	TRT	REP	Depth (cm)	Labile C (μg g^{-1})	Stable C (μg g^{-1})	Inert C (1M) (μg g^{-1})	Inert C(6M) (μg g^{-1})
1916	CNT	1	0-5	43.5		346.5	133.7
1916	CNT	1	5-15	20.0	55.0	198.4	61.4
1922	CNT	2	0-5	23.0	39.4	202.8	68.7
1922	CNT	2	5-15	21.8	64.2	383.3	146.1
1928	CNT	3	0-5	13.2	48.2	38.3	14.6
1928	CNT	3	5-15	19.4	44.5	80.1	14.4
1917	S1	1	0-5	33.0	80.3	283.1	94.2
1917	S1	1	5-15	14.7	37.2	177.4	48.6
1921	S1	2	0-5	26.9	77.3	269.8	132.3
1921	S1	2	5-15	15.1	31.5	197.4	65.9
1924	S1	3	0-5	22.1	60.8	314.2	73.5
1924	S1	3	5-15	12.3	31.7	518.8	107.7
1913	S2	2	0-5	20.6	60.6	313.9	118.3
1913	S2	2	5-15	12.1	34.4	148.1	59.8
1918	S2	1	0-5	33.4	108.4	289.9	106.9
1918	S2	1	5-15	19.4	57.5	190.6	55.0
1926	S2	3	0-5	18.2	59.0	181.0	71.9
1926	S2	3	5-15	14.1	36.6	72.0	22.9
1915	S3	1	0-5	34.1	99.9	425.7	149.4
1915	S3	1	5-15	17.0	40.2	221.7	99.3
1920	S3	2	0-5	27.6	98.7	544.6	179.3
1920	S3	2	5-15	14.1	39.9	152.0	73.9
1930	S3	3	0-5	16.0	56.9	94.6	37.4
1930	S3	3	5-15	16.5	41.2	76.6	20.9
1919	S4	1	0-5	28.2	81.6	248.7	102.5
1919	S4	1	5-15	16.2	43.7	167.3	66.0
1927	S4	2	0-5	13.1	38.1	40.7	14.1
1927	S4	2	5-15	11.5	29.7	42.7	15.1
1929	S4	3	0-5	22.8	92.8	432.1	113.6
1929	S4	3	5-15	16.5	57.1	219.1	98.8
1914	S5	1	0-5	27.6	110.1	437.9	150.9
1914	S5	1	5-15	15.9	37.8	155.0	76.3
1923	S5	2	0-5	24.6	77.3	452.9	154.3
1923	S5	2	5-15	16.3	35.4	332.4	96.3
1925	S5	3	0-5	25.7	57.3		112.4
1925	S5	3	5-15	13.8	36.8	90.9	24.4

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.8 Soil nitrogen fraction (μg g^{-1}) for 0-5 and 5-15 cm depths in 2016. TRT, treatment; REP, replication.

Plot ID	TRT	REP	Depth (cm)	Labile N (μg g^{-1})	Stable N (μg g^{-1})	Inert N (1M) (μg g^{-1})	Inert N (6M) (μg g^{-1})
1916	CNT	1	0-5	4.69	14.37	50.8	23.0
1916	CNT	1	5-15	2.29	5.54	28.9	12.9
1922	CNT	2	0-5	2.66	4.40	48.6	12.9
1922	CNT	2	5-15	2.88	7.95	59.3	27.7
1928	CNT	3	0-5	1.94	4.79	6.4	2.6
1928	CNT	3	5-15	1.34	3.06	10.8	2.4
1917	S1	1	0-5	2.38	8.88	43.9	19.3
1917	S1	1	5-15	1.79	4.67	26.3	8.9
1921	S1	2	0-5	3.63	9.51	43.1	25.8
1921	S1	2	5-15	2.19	3.70	28.1	13.1
1924	S1	3	0-5	2.44	6.15	42.3	14.9
1924	S1	3	5-15	1.85	3.04	69.5	22.1
1913	S2	2	0-5	2.91	5.89	46.4	20.6
1913	S2	2	5-15	1.32	3.59	19.8	11.7
1918	S2	1	0-5	4.32	14.48	47.3	23.0
1918	S2	1	5-15	2.25	5.80	28.1	10.1
1926	S2	3	0-5	2.87	6.18	24.8	12.3
1926	S2	3	5-15	1.73	3.30	10.2	4.2
1915	S3	1	0-5	4.94	9.91	60.5	25.8
1915	S3	1	5-15	2.02	4.76	32.1	20.2
1920	S3	2	0-5	3.09	11.27	84.3	30.7
1920	S3	2	5-15	1.63	4.50	21.6	13.7
1930	S3	3	0-5	1.58	5.81	12.9	6.7
1930	S3	3	5-15	1.09	3.16	7.7	3.6
1919	S4	1	0-5	2.91	9.16	41.0	21.5
1919	S4	1	5-15	2.06	4.27	23.5	12.6
1927	S4	2	0-5	2.17	3.77	6.5	2.6
1927	S4	2	5-15	1.40	2.24	5.8	2.5
1929	S4	3	0-5	4.37	9.47	60.4	20.6
1929	S4	3	5-15	3.18	5.97	30.5	19.8
1914	S5	1	0-5		9.91	60.2	26.1
1914	S5	1	5-15	2.47	4.23	20.8	14.7
1923	S5	2	0-5	4.15	9.02	70.5	30.8
1923	S5	2	5-15	2.27	3.44	49.1	21.2
1925	S5	3	0-5	1.86	6.19		22.5
1925	S5	3	5-15	2.57	3.45	14.1	4.5

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5).

A1.9 Soil bulk density (Mg m^{-3}) for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths in 2017. TRT, treatment; GRZ, grazing; REP, replication; BD, bulk density.

Plot ID	TRT	GRZ	REP	Depth (cm)	BD (Mg m^{-3})
1916	CTN	UG	1	0-5	1.07
1916	CTN	UG	1	0-5	1.06
1916	CTN	UG	1	5-15	1.28
1916	CTN	UG	1	5-15	1.30
1916	CTN	UG	1	15-30	1.26
1916	CTN	UG	1	15-30	1.31
1916	CTN	UG	1	30-45	1.27
1916	CTN	UG	1	30-45	1.45
1916	CTN	UG	1	45-60	1.46
1916	CTN	UG	1	45-60	1.50
1922	CTN	UG	2	0-5	1.10
1922	CTN	UG	2	0-5	1.22
1922	CTN	UG	2	5-15	1.46
1922	CTN	UG	2	5-15	1.26
1922	CTN	UG	2	15-30	1.32
1922	CTN	UG	2	15-30	1.33
1922	CTN	UG	2	30-45	1.33
1922	CTN	UG	2	30-45	1.43
1922	CTN	UG	2	45-60	1.31
1922	CTN	UG	2	45-60	1.34
1928	CTN	UG	3	0-5	1.03
1928	CTN	UG	3	0-5	1.11
1928	CTN	UG	3	5-15	1.54
1928	CTN	UG	3	5-15	1.71
1928	CTN	UG	3	15-30	1.52
1928	CTN	UG	3	15-30	1.57
1928	CTN	UG	3	30-45	1.67
1928	CTN	UG	3	30-45	1.33
1928	CTN	UG	3	45-60	1.60
1928	CTN	UG	3	45-60	1.58
1917	S1	UG	1	0-5	
1917	S1	UG	1	0-5	1.44
1917	S1	UG	1	5-15	1.39
1917	S1	UG	1	5-15	1.50
1917	S1	UG	1	15-30	1.34
1917	S1	UG	1	15-30	1.41
1917	S1	UG	1	30-45	1.35
1917	S1	UG	1	30-45	1.39

A1.9 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	BD (Mg m^{-3})
1917	S1	UG	1	45-60	1.48
1917	S1	UG	1	45-60	1.39
1921	S1	UG	2	0-5	1.26
1921	S1	UG	2	0-5	1.26
1921	S1	UG	2	5-15	1.50
1921	S1	UG	2	5-15	1.31
1921	S1	UG	2	15-30	1.32
1921	S1	UG	2	15-30	1.37
1921	S1	UG	2	30-45	1.21
1921	S1	UG	2	30-45	1.24
1921	S1	UG	2	45-60	1.28
1921	S1	UG	2	45-60	1.20
1924	S1	UG	3	0-5	1.47
1924	S1	UG	3	0-5	1.34
1924	S1	UG	3	5-15	1.70
1924	S1	UG	3	5-15	1.61
1924	S1	UG	3	15-30	1.54
1924	S1	UG	3	15-30	1.54
1924	S1	UG	3	30-45	1.39
1924	S1	UG	3	30-45	1.22
1924	S1	UG	3	45-60	1.49
1924	S1	UG	3	45-60	1.20
1913	S2	UG	2	0-5	1.01
1913	S2	UG	2	0-5	1.19
1913	S2	UG	2	5-15	1.29
1913	S2	UG	2	5-15	1.45
1913	S2	UG	2	15-30	1.29
1913	S2	UG	2	15-30	1.35
1913	S2	UG	2	30-45	1.49
1913	S2	UG	2	30-45	1.46
1913	S2	UG	2	45-60	1.45
1913	S2	UG	2	45-60	1.41
1918	S2	UG	1	0-5	0.97
1918	S2	UG	1	0-5	1.12
1918	S2	UG	1	5-15	1.44
1918	S2	UG	1	5-15	1.47
1918	S2	UG	1	15-30	1.33
1918	S2	UG	1	15-30	1.34
1918	S2	UG	1	30-45	1.35

A1.9 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	BD (Mg m^{-3})
1918	S2	UG	1	30-45	1.41
1918	S2	UG	1	45-60	1.38
1918	S2	UG	1	45-60	1.38
1926	S2	UG	3	0-5	0.95
1926	S2	UG	3	0-5	1.42
1926	S2	UG	3	5-15	1.34
1926	S2	UG	3	5-15	1.49
1926	S2	UG	3	15-30	1.28
1926	S2	UG	3	15-30	1.40
1926	S2	UG	3	30-45	1.39
1926	S2	UG	3	30-45	1.39
1926	S2	UG	3	45-60	1.42
1926	S2	UG	3	45-60	1.38
1915	S3	G	1	0-5	1.08
1915	S3	G	1	0-5	1.42
1915	S3	G	1	5-15	1.37
1915	S3	G	1	5-15	1.26
1915	S3	G	1	15-30	1.24
1915	S3	G	1	15-30	1.17
1915	S3	G	1	30-45	1.33
1915	S3	G	1	30-45	1.24
1915	S3	G	1	45-60	1.36
1915	S3	G	1	45-60	1.56
1920	S3	G	2	0-5	1.15
1920	S3	G	2	0-5	1.26
1920	S3	G	2	5-15	1.32
1920	S3	G	2	5-15	1.38
1920	S3	G	2	15-30	1.24
1920	S3	G	2	15-30	1.28
1920	S3	G	2	30-45	1.37
1920	S3	G	2	30-45	1.38
1920	S3	G	2	45-60	1.32
1920	S3	G	2	45-60	1.29
1930	S3	G	3	0-5	1.29
1930	S3	G	3	0-5	1.60
1930	S3	G	3	5-15	1.44
1930	S3	G	3	5-15	1.42
1930	S3	G	3	15-30	1.41
1930	S3	G	3	15-30	1.64

A1.9 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	BD (Mg m^{-3})
1930	S3	G	3	30-45	1.45
1930	S3	G	3	30-45	1.40
1930	S3	G	3	45-60	1.45
1930	S3	G	3	45-60	1.67
1915	S3	UG	1	0-5	1.02
1915	S3	UG	1	0-5	1.04
1915	S3	UG	1	5-15	1.40
1915	S3	UG	1	5-15	1.28
1915	S3	UG	1	15-30	1.26
1915	S3	UG	1	15-30	1.30
1915	S3	UG	1	30-45	1.29
1915	S3	UG	1	30-45	1.36
1915	S3	UG	1	45-60	1.33
1915	S3	UG	1	45-60	1.52
1920	S3	UG	2	0-5	1.07
1920	S3	UG	2	0-5	0.87
1920	S3	UG	2	5-15	1.25
1920	S3	UG	2	5-15	1.39
1920	S3	UG	2	15-30	1.23
1920	S3	UG	2	15-30	1.27
1920	S3	UG	2	30-45	1.32
1920	S3	UG	2	30-45	1.35
1920	S3	UG	2	45-60	1.40
1920	S3	UG	2	45-60	1.27
1930	S3	UG	3	0-5	1.03
1930	S3	UG	3	0-5	1.00
1930	S3	UG	3	5-15	1.32
1930	S3	UG	3	5-15	1.25
1930	S3	UG	3	15-30	1.34
1930	S3	UG	3	15-30	1.43
1930	S3	UG	3	30-45	1.50
1930	S3	UG	3	30-45	1.52
1930	S3	UG	3	45-60	1.84
1930	S3	UG	3	45-60	1.73
1919	S4	G	1	0-5	1.06
1919	S4	G	1	0-5	1.48
1919	S4	G	1	5-15	1.31
1919	S4	G	1	5-15	1.41
1919	S4	G	1	15-30	1.34

A1.9 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	BD (Mg m^{-3})
1919	S4	G	1	15-30	1.34
1919	S4	G	1	30-45	1.33
1919	S4	G	1	30-45	1.28
1919	S4	G	1	45-60	1.31
1919	S4	G	1	45-60	1.33
1927	S4	G	2	0-5	1.53
1927	S4	G	2	0-5	1.71
1927	S4	G	2	5-15	1.50
1927	S4	G	2	5-15	1.52
1927	S4	G	2	15-30	1.36
1927	S4	G	2	15-30	1.44
1927	S4	G	2	30-45	1.43
1927	S4	G	2	30-45	1.36
1927	S4	G	2	45-60	1.51
1927	S4	G	2	45-60	1.53
1929	S4	G	3	0-5	1.12
1929	S4	G	3	0-5	1.19
1929	S4	G	3	5-15	1.27
1929	S4	G	3	5-15	1.24
1929	S4	G	3	15-30	1.25
1929	S4	G	3	15-30	1.27
1929	S4	G	3	30-45	1.14
1929	S4	G	3	30-45	1.21
1929	S4	G	3	45-60	1.15
1929	S4	G	3	45-60	1.43
1919	S4	UG	1	0-5	1.00
1919	S4	UG	1	0-5	0.88
1919	S4	UG	1	5-15	1.36
1919	S4	UG	1	5-15	1.33
1919	S4	UG	1	15-30	1.26
1919	S4	UG	1	15-30	1.38
1919	S4	UG	1	30-45	1.31
1919	S4	UG	1	30-45	1.43
1919	S4	UG	1	45-60	1.45
1919	S4	UG	1	45-60	1.45
1927	S4	UG	2	0-5	1.32
1927	S4	UG	2	0-5	1.34
1927	S4	UG	2	5-15	1.58
1927	S4	UG	2	5-15	1.52

A1.9 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	BD (Mg m^{-3})
1927	S4	UG	2	15-30	1.47
1927	S4	UG	2	15-30	1.31
1927	S4	UG	2	30-45	1.22
1927	S4	UG	2	30-45	1.35
1927	S4	UG	2	45-60	1.26
1927	S4	UG	2	45-60	1.41
1929	S4	UG	3	0-5	1.06
1929	S4	UG	3	0-5	0.86
1929	S4	UG	3	5-15	1.29
1929	S4	UG	3	5-15	1.33
1929	S4	UG	3	15-30	1.13
1929	S4	UG	3	15-30	1.20
1929	S4	UG	3	30-45	1.10
1929	S4	UG	3	30-45	1.00
1929	S4	UG	3	45-60	1.53
1929	S4	UG	3	45-60	1.36
1914	S5	G	1	0-5	0.98
1914	S5	G	1	0-5	0.97
1914	S5	G	1	5-15	1.25
1914	S5	G	1	5-15	1.12
1914	S5	G	1	15-30	1.29
1914	S5	G	1	15-30	1.36
1914	S5	G	1	30-45	1.38
1914	S5	G	1	30-45	1.46
1914	S5	G	1	45-60	1.45
1914	S5	G	1	45-60	1.47
1923	S5	G	2	0-5	1.42
1923	S5	G	2	0-5	1.36
1923	S5	G	2	5-15	1.50
1923	S5	G	2	5-15	1.42
1923	S5	G	2	15-30	1.46
1923	S5	G	2	15-30	1.34
1923	S5	G	2	30-45	1.45
1923	S5	G	2	30-45	1.25
1923	S5	G	2	45-60	1.38
1923	S5	G	2	45-60	1.35
1925	S5	G	3	0-5	1.68
1925	S5	G	3	0-5	0.96
1925	S5	G	3	5-15	1.54

A1.9 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	BD (Mg m^{-3})
1925	S5	G	3	5-15	1.65
1925	S5	G	3	15-30	1.47
1925	S5	G	3	15-30	1.43
1925	S5	G	3	30-45	1.39
1925	S5	G	3	30-45	1.48
1925	S5	G	3	45-60	1.43
1925	S5	G	3	45-60	1.52
1914	S5	UG	1	0-5	1.23
1914	S5	UG	1	0-5	1.08
1914	S5	UG	1	5-15	1.40
1914	S5	UG	1	5-15	1.35
1914	S5	UG	1	15-30	1.29
1914	S5	UG	1	15-30	1.20
1914	S5	UG	1	30-45	1.46
1914	S5	UG	1	30-45	1.37
1914	S5	UG	1	45-60	1.51
1914	S5	UG	1	45-60	1.32
1923	S5	UG	2	0-5	1.23
1923	S5	UG	2	0-5	1.36
1923	S5	UG	2	5-15	1.61
1923	S5	UG	2	5-15	
1923	S5	UG	2	15-30	1.40
1923	S5	UG	2	15-30	1.50
1923	S5	UG	2	30-45	1.40
1923	S5	UG	2	30-45	1.25
1923	S5	UG	2	45-60	1.43
1923	S5	UG	2	45-60	1.42
1925	S5	UG	3	0-5	1.08
1925	S5	UG	3	0-5	1.27
1925	S5	UG	3	5-15	1.55
1925	S5	UG	3	5-15	1.51
1925	S5	UG	3	15-30	1.49
1925	S5	UG	3	15-30	1.46
1925	S5	UG	3	30-45	1.44
1925	S5	UG	3	30-45	1.49
1925	S5	UG	3	45-60	1.44
1925	S5	UG	3	45-60	1.41

A1.10 Soil pH and electrical conductivity (dS m^{-1}) for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths in 2017. TRT, treatment; GRZ, grazing; REP, replication; EC, electrical conductivity.

Plot ID	TRT	GRZ	REP	Depth (cm)	pH	EC (dS m^{-1})
1916	CNT	UG	1	0-5	5.55	0.162
1916	CNT	UG	1	5-15	4.87	0.140
1916	CNT	UG	1	15-30	6.04	0.174
1916	CNT	UG	1	30-45	6.77	0.231
1916	CNT	UG	1	45-60	7.55	0.314
1922	CNT	UG	2	0-5	5.72	0.145
1922	CNT	UG	2	5-15	4.98	0.101
1922	CNT	UG	2	15-30	5.81	0.120
1922	CNT	UG	2	30-45	6.76	0.213
1922	CNT	UG	2	45-60	7.73	0.302
1928	CNT	UG	3	0-5	6.01	0.066
1928	CNT	UG	3	5-15	5.67	0.067
1928	CNT	UG	3	15-30	7.37	0.204
1928	CNT	UG	3	30-45	7.77	0.165
1928	CNT	UG	3	45-60	8.19	0.133
1917	S1	UG	1	0-5	5.98	0.212
1917	S1	UG	1	5-15	5.40	0.123
1917	S1	UG	1	15-30	5.40	0.187
1917	S1	UG	1	30-45	6.77	0.176
1917	S1	UG	1	45-60	7.65	0.270
1921	S1	UG	2	0-5	6.05	0.164
1921	S1	UG	2	5-15	5.93	0.139
1921	S1	UG	2	15-30	7.14	0.200
1921	S1	UG	2	30-45	7.45	0.231
1921	S1	UG	2	45-60	7.49	0.295
1924	S1	UG	3	0-5	7.89	0.214
1924	S1	UG	3	5-15	8.07	0.156
1924	S1	UG	3	15-30	7.75	0.196
1924	S1	UG	3	30-45	7.94	0.183
1924	S1	UG	3	45-60	7.98	0.168
1913	S2	UG	2	0-5	6.94	0.278
1913	S2	UG	2	5-15	5.63	0.158
1913	S2	UG	2	15-30	6.42	0.205
1913	S2	UG	2	30-45	6.93	0.225
1913	S2	UG	2	45-60	7.63	0.321

A1.10 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	pH	EC (dS m^{-1})
1918	S2	UG	1	0-5	5.55	0.146
1918	S2	UG	1	5-15	5.42	0.093
1918	S2	UG	1	15-30	6.33	0.151
1918	S2	UG	1	30-45	6.89	0.240
1918	S2	UG	1	45-60	7.97	0.255
1926	S2	UG	3	0-5	5.45	0.133
1926	S2	UG	3	5-15	4.84	0.098
1926	S2	UG	3	15-30	6.16	0.202
1926	S2	UG	3	30-45	7.36	0.178
1926	S2	UG	3	45-60	7.61	0.314
1915	S3	G	1	0-5	5.04	0.390
1915	S3	G	1	5-15	4.95	0.183
1915	S3	G	1	15-30	6.39	0.183
1915	S3	G	1	30-45	7.67	0.307
1915	S3	G	1	45-60	8.16	0.272
1920	S3	G	2	0-5	5.45	0.137
1920	S3	G	2	5-15	5.52	0.145
1920	S3	G	2	15-30	6.48	0.217
1920	S3	G	2	30-45	6.73	0.186
1920	S3	G	2	45-60	7.59	0.283
1930	S3	G	3	0-5	7.79	0.226
1930	S3	G	3	5-15	8.00	0.198
1930	S3	G	3	15-30	8.30	0.134
1930	S3	G	3	30-45	8.43	0.015
1930	S3	G	3	45-60	8.32	0.121
1915	S3	UG	1	0-5	5.46	0.178
1915	S3	UG	1	5-15	5.24	0.125
1915	S3	UG	1	15-30	6.39	0.149
1915	S3	UG	1	30-45	7.65	0.291
1915	S3	UG	1	45-60	8.26	0.262
1920	S3	UG	2	0-5	6.30	0.246
1920	S3	UG	2	5-15	5.34	0.133
1920	S3	UG	2	15-30	6.26	0.174
1920	S3	UG	2	30-45	6.64	0.166
1920	S3	UG	2	45-60	7.24	0.260
1930	S3	UG	3	0-5	7.84	0.199
1930	S3	UG	3	5-15	7.96	0.184
1930	S3	UG	3	15-30	8.37	0.130
1930	S3	UG	3	30-45	8.26	0.124

A1.10 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	pH	EC (dS m^{-1})
1930	S3	G	3	45-60	8.32	0.121
1915	S3	UG	1	0-5	5.46	0.178
1915	S3	UG	1	5-15	5.24	0.125
1915	S3	UG	1	15-30	6.39	0.149
1915	S3	UG	1	30-45	7.65	0.291
1915	S3	UG	1	45-60	8.26	0.262
1920	S3	UG	2	0-5	6.30	0.246
1920	S3	UG	2	5-15	5.34	0.133
1920	S3	UG	2	15-30	6.26	0.174
1920	S3	UG	2	30-45	6.64	0.166
1920	S3	UG	2	45-60	7.24	0.260
1930	S3	UG	3	0-5	7.84	0.199
1930	S3	UG	3	5-15	7.96	0.184
1930	S3	UG	3	15-30	8.37	0.130
1930	S3	UG	3	30-45	8.26	0.124
1930	S3	UG	3	45-60	8.28	0.118
1919	S4	G	1	0-5	5.62	0.147
1919	S4	G	1	5-15	5.33	0.104
1919	S4	G	1	15-30	6.46	0.157
1919	S4	G	1	30-45	8.09	0.286
1919	S4	G	1	45-60	8.29	0.240
1927	S4	G	2	0-5	5.46	0.116
1927	S4	G	2	5-15	5.25	0.088
1927	S4	G	2	15-30	6.19	0.110
1927	S4	G	2	30-45	6.66	0.152
1927	S4	G	2	45-60	7.06	0.187
1929	S4	G	3	0-5	5.55	0.139
1929	S4	G	3	5-15	5.67	0.133
1929	S4	G	3	15-30	6.07	0.116
1929	S4	G	3	30-45	6.30	0.111
1929	S4	G	3	45-60	6.38	0.124
1919	S4	UG	1	0-5	5.48	0.210
1919	S4	UG	1	5-15	5.31	0.132
1919	S4	UG	1	15-30	6.57	0.207
1919	S4	UG	1	30-45	7.74	0.263
1919	S4	UG	1	45-60	8.33	0.207
1927	S4	UG	2	0-5	5.31	0.129
1927	S4	UG	2	5-15	4.70	0.080
1927	S4	UG	2	15-30	6.09	0.094

A1.10 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	pH	EC (dS m^{-1})
1927	S4	UG	2	30-45	6.58	0.142
1927	S4	UG	2	45-60	7.20	0.284
1929	S4	UG	3	0-5	5.90	0.155
1929	S4	UG	3	5-15	5.52	0.130
1929	S4	UG	3	15-30	5.92	0.091
1929	S4	UG	3	30-45	6.02	0.122
1929	S4	UG	3	45-60	6.18	0.115
1914	S5	G	1	0-5	5.34	0.204
1914	S5	G	1	5-15	5.27	0.131
1914	S5	G	1	15-30	6.22	0.173
1914	S5	G	1	30-45	6.87	0.191
1914	S5	G	1	45-60	7.86	0.294
1923	S5	G	2	0-5	6.79	0.334
1923	S5	G	2	5-15	5.10	0.117
1923	S5	G	2	15-30	6.04	0.125
1923	S5	G	2	30-45	6.86	0.161
1923	S5	G	2	45-60	7.40	0.216
1925	S5	G	3	0-5	5.72	0.285
1925	S5	G	3	5-15	5.21	0.119
1925	S5	G	3	15-30	6.31	0.129
1925	S5	G	3	30-45	6.75	0.125
1925	S5	G	3	45-60	7.12	0.192
1914	S5	UG	1	0-5	5.64	0.179
1914	S5	UG	1	5-15	5.16	0.113
1914	S5	UG	1	15-30	6.18	0.147
1914	S5	UG	1	30-45	6.83	0.240
1914	S5	UG	1	45-60	7.80	0.316
1923	S5	UG	2	0-5	6.52	0.186
1923	S5	UG	2	5-15	5.76	0.118
1923	S5	UG	2	15-30	6.99	0.188
1923	S5	UG	2	30-45	7.61	0.225
1923	S5	UG	2	45-60	7.78	0.213
1925	S5	UG	3	0-5	5.93	0.102
1925	S5	UG	3	5-15	5.15	0.069
1925	S5	UG	3	15-30	6.26	0.089
1925	S5	UG	3	30-45	6.75	0.135
1925	S5	UG	3	45-60	7.59	0.231

A1.11 Soil organic carbon (g kg^{-1}) and total nitrogen (g kg^{-1}) for 0-5, 5-15, 15-30, 30-45, and 45-60 cm depths in 2017. TRT, treatment; GRZ, grazing; REP, replication; SOC, soil organic carbon; TN, total nitrogen.

Plot ID	TRT	GRZ	REP	Depth (cm)	SOC (g kg^{-1})	TN (g kg^{-1})
1916	CNT	UG	1	0-5	35.19	3.12
1916	CNT	UG	1	5-15	21.10	1.94
1916	CNT	UG	1	15-30	17.20	1.54
1916	CNT	UG	1	30-45	12.20	1.12
1916	CNT	UG	1	45-60	11.20	1.09
1922	CNT	UG	2	0-5	25.29	2.29
1922	CNT	UG	2	5-15	16.90	1.61
1922	CNT	UG	2	15-30	13.80	1.26
1922	CNT	UG	2	30-45	11.60	1.06
1922	CNT	UG	2	45-60	15.35	1.00
1928	CNT	UG	3	0-5	9.90	1.12
1928	CNT	UG	3	5-15	7.09	0.82
1928	CNT	UG	3	15-30	4.39	0.58
1928	CNT	UG	3	30-45	5.48	0.49
1928	CNT	UG	3	45-60	6.77	0.40
1917	S1	UG	1	0-5	30.40	2.72
1917	S1	UG	1	5-15	21.59	1.99
1917	S1	UG	1	15-30	15.20	1.45
1917	S1	UG	1	30-45	11.09	1.16
1917	S1	UG	1	45-60	11.39	1.09
1921	S1	UG	2	0-5	24.30	2.29
1921	S1	UG	2	5-15	15.10	1.38
1921	S1	UG	2	15-30	12.59	1.17
1921	S1	UG	2	30-45	15.20	1.14
1921	S1	UG	2	45-60	21.48	1.22
1924	S1	UG	3	0-5	25.98	0.69
1924	S1	UG	3	5-15	22.29	0.51
1924	S1	UG	3	15-30	19.65	0.89
1924	S1	UG	3	30-45	35.42	0.84
1924	S1	UG	3	45-60	23.19	0.59
1913	S2	UG	2	0-5	27.70	2.37
1913	S2	UG	2	5-15	21.30	1.93
1913	S2	UG	2	15-30	16.50	1.54
1913	S2	UG	2	30-45	13.29	1.32
1913	S2	UG	2	45-60	13.09	1.23

A1.11 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	SOC (g kg^{-1})	TN (g kg^{-1})
1918	S2	UG	1	0-5	27.70	2.53
1918	S2	UG	1	5-15	18.89	1.71
1918	S2	UG	1	15-30	18.29	1.64
1918	S2	UG	1	30-45	12.29	1.19
1918	S2	UG	1	45-60	17.87	1.03
1926	S2	UG	3	0-5	21.60	2.13
1926	S2	UG	3	5-15	15.29	1.54
1926	S2	UG	3	15-30	12.49	1.20
1926	S2	UG	3	30-45	12.60	1.17
1926	S2	UG	3	45-60	17.57	1.16
1915	S3	G	1	0-5	31.60	2.87
1915	S3	G	1	5-15	20.10	1.89
1915	S3	G	1	15-30	13.69	1.34
1915	S3	G	1	30-45	13.60	1.13
1915	S3	G	1	45-60	21.74	0.94
1920	S3	G	2	0-5	26.79	2.40
1920	S3	G	2	5-15	21.49	1.96
1920	S3	G	2	15-30	16.30	1.53
1920	S3	G	2	30-45	10.99	1.17
1920	S3	G	2	45-60	13.88	0.99
1930	S3	G	3	0-5	44.23	1.91
1930	S3	G	3	5-15	35.63	1.22
1930	S3	G	3	15-30	43.74	0.82
1930	S3	G	3	30-45	53.77	0.48
1930	S3	G	3	45-60	36.48	0.30
1915	S3	UG	1	0-5	29.20	2.61
1915	S3	UG	1	5-15	19.39	1.86
1915	S3	UG	1	15-30	14.10	1.40
1915	S3	UG	1	30-45	12.99	1.14
1915	S3	UG	1	45-60	22.13	0.99
1920	S3	UG	2	0-5	31.90	2.71
1920	S3	UG	2	5-15	23.00	1.95
1920	S3	UG	2	15-30	17.30	1.59
1920	S3	UG	2	30-45	11.80	1.17
1920	S3	UG	2	45-60	10.70	1.08
1930	S3	UG	3	0-5	39.29	2.13
1930	S3	UG	3	5-15	40.79	1.19
1930	S3	UG	3	15-30	52.09	0.66
1930	S3	UG	3	30-45	26.24	0.31

A1.11 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	SOC (g kg^{-1})	TN (g kg^{-1})
1930	S3	UG	3	45-60	4.48	0.29
1919	S4	G	1	0-5	26.29	2.42
1919	S4	G	1	5-15	19.40	1.74
1919	S4	G	1	15-30	11.89	1.24
1919	S4	G	1	30-45	15.27	1.11
1919	S4	G	1	45-60	21.14	0.90
1927	S4	G	2	0-5	17.20	1.66
1927	S4	G	2	5-15	9.79	1.05
1927	S4	G	2	15-30	12.29	1.18
1927	S4	G	2	30-45	9.59	0.96
1927	S4	G	2	45-60	8.49	0.86
1929	S4	G	3	0-5	32.30	2.85
1929	S4	G	3	5-15	25.79	2.30
1929	S4	G	3	15-30	25.50	2.21
1929	S4	G	3	30-45	20.60	1.77
1929	S4	G	3	45-60	12.09	1.23
1919	S4	UG	1	0-5	34.70	3.05
1919	S4	UG	1	5-15	18.00	1.73
1919	S4	UG	1	15-30	12.29	1.26
1919	S4	UG	1	30-45	14.58	1.18
1919	S4	UG	1	45-60	23.62	0.83
1927	S4	UG	2	0-5	18.00	1.75
1927	S4	UG	2	5-15	9.20	1.03
1927	S4	UG	2	15-30	13.20	1.28
1927	S4	UG	2	30-45	11.00	1.12
1927	S4	UG	2	45-60	10.70	0.98
1929	S4	UG	3	0-5	35.79	3.19
1929	S4	UG	3	5-15	25.98	2.34
1929	S4	UG	3	15-30	26.99	2.31
1929	S4	UG	3	30-45	23.50	2.03
1929	S4	UG	3	45-60	14.39	1.32
1914	S5	G	1	0-5	29.50	2.69
1914	S5	G	1	5-15	22.09	2.06
1914	S5	G	1	15-30	15.39	1.54
1914	S5	G	1	30-45	10.79	1.18
1914	S5	G	1	45-60	12.79	1.07
1923	S5	G	2	0-5	21.99	2.01
1923	S5	G	2	5-15	15.89	1.49
1923	S5	G	2	15-30	12.30	1.21

A1.11 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	SOC (g kg^{-1})	TN (g kg^{-1})
1923	S5	G	2	30-45	8.40	0.87
1923	S5	G	2	45-60	8.19	0.81
1925	S5	G	3	0-5	14.70	1.49
1925	S5	G	3	5-15	10.19	0.97
1925	S5	G	3	15-30	6.99	0.83
1925	S5	G	3	30-45	6.20	0.58
1925	S5	G	3	45-60	7.90	0.79
1914	S5	UG	1	0-5	31.09	2.82
1914	S5	UG	1	5-15	20.89	1.91
1914	S5	UG	1	15-30	14.59	1.50
1914	S5	UG	1	30-45	11.70	1.21
1914	S5	UG	1	45-60	12.78	1.11
1923	S5	UG	2	0-5	25.60	2.36
1923	S5	UG	2	5-15	15.50	1.40
1923	S5	UG	2	15-30	9.70	0.95
1923	S5	UG	2	30-45	8.20	0.84
1923	S5	UG	2	45-60	8.29	0.78
1925	S5	UG	3	0-5	14.39	1.47
1925	S5	UG	3	5-15	9.99	1.06
1925	S5	UG	3	15-30	7.89	0.90
1925	S5	UG	3	30-45	7.29	0.83
1925	S5	UG	3	45-60	8.69	0.78

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5). G: Grazed; UG: Un-grazed.

A1.12 Wet soil aggregate stability (%) for 0-5, and 5-15 cm depths in 2017. TRT, treatment; REP, replication; GRZ, grazing; WAS, wet soil aggregate stability.

Plot ID	TRT	GRZ	REP	Depth (cm)	WAS (%)
1916	CNT	UG	1	0-5	87.8
1916	CNT	UG	1	5-15	90.7
1922	CNT	UG	2	0-5	96.3
1922	CNT	UG	2	5-15	93.2
1928	CNT	UG	3	0-5	71.5
1928	CNT	UG	3	5-15	84.8
1917	S1	UG	1	0-5	88.3
1917	S1	UG	1	5-15	91.3
1921	S1	UG	2	0-5	99.2
1921	S1	UG	2	5-15	99.6
1924	S1	UG	3	0-5	69.7
1924	S1	UG	3	5-15	96.9
1913	S2	UG	2	0-5	99.7
1913	S2	UG	2	5-15	93.4
1918	S2	UG	1	0-5	98.9
1918	S2	UG	1	5-15	88.3
1926	S2	UG	3	0-5	90.5
1926	S2	UG	3	5-15	83.2
1915	S3	G	1	0-5	99.7
1915	S3	G	1	5-15	91.1
1920	S3	G	2	0-5	99.7
1920	S3	G	2	5-15	93.1
1930	S3	G	3	0-5	94.9
1930	S3	G	3	5-15	94.7
1915	S3	UG	1	0-5	95.8
1915	S3	UG	1	5-15	99.0
1920	S3	UG	2	0-5	97.6
1920	S3	UG	2	5-15	97.9
1930	S3	UG	3	0-5	89.8
1930	S3	UG	3	5-15	88.7
1919	S4	G	1	0-5	99.7
1919	S4	G	1	5-15	95.8
1927	S4	G	2	0-5	81.6
1927	S4	G	2	5-15	90.2
1929	S4	G	3	0-5	99.6
1929	S4	G	3	5-15	92.3
1919	S4	UG	1	0-5	99.7
1919	S4	UG	1	5-15	93.0

A1.12 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	WAS (%)
1927	S4	UG	2	0-5	98.8
1927	S4	UG	2	5-15	92.4
1929	S4	UG	3	0-5	99.7
1929	S4	UG	3	5-15	94.4
1914	S5	G	1	0-5	94.6
1914	S5	G	1	5-15	96.6
1923	S5	G	2	0-5	99.3
1923	S5	G	2	5-15	94.5
1925	S5	G	3	0-5	54.6
1925	S5	G	3	5-15	80.5
1914	S5	UG	1	0-5	99.0
1914	S5	UG	1	5-15	91.2
1923	S5	UG	2	0-5	94.9
1923	S5	UG	2	5-15	93.9
1925	S5	UG	3	0-5	74.1
1925	S5	UG	3	5-15	85.9

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5). G: Grazed; UG: Un-grazed.

A1.13 Soil water retention (m^3 m^{-3}) for 0-5 cm depth in 2017. TRT, treatment; GRZ, grazing; REP, replication;

Plot ID	TRT	GRZ	REP	0	0.4	1	2.5	5	10	30
				(-kPa)						
1916-1	CNT	UG	1	0.591	0.585	0.581	0.576	0.570	0.456	0.436
1916-2	CNT	UG	1	0.563	0.560	0.558	0.555	0.553	0.464	0.450
1922-1	CNT	UG	2	0.533	0.528	0.527	0.524	0.520	0.379	0.371
1922-2	CNT	UG	2	0.536	0.530	0.526	0.523	0.519	0.381	0.356
1928-1	CNT	UG	3	0.528	0.522	0.520	0.516	0.512	0.361	0.293
1917-1	S1	UG	1	0.566	0.564	0.559	0.556	0.553	0.407	0.396
1917-2	S1	UG	1	0.595	0.585	0.582	0.578	0.577	0.470	0.449
1921-1	S1	UG	2	0.522	0.515	0.512	0.508	0.505	0.360	0.340
1921-2	S1	UG	2	0.572	0.567	0.561	0.555	0.551	0.374	0.346
1924-1	S1	UG	3	0.509	0.505	0.502	0.500	0.496	0.349	0.322
1924-2	S1	UG	3	0.520	0.515	0.510	0.507	0.502	0.338	0.305
1913-1	S2	UG	2	0.576	0.570	0.566	0.561	0.555	0.369	0.355
1913-2	S2	UG	2	0.603	0.599	0.596	0.593	0.589	0.415	0.396
1918-1	S2	UG	1	0.585	0.576	0.571	0.569	0.563	0.454	0.426
1918-2	S2	UG	1	0.513	0.509	0.505	0.501	0.499	0.382	0.375
1926-1	S2	UG	3	0.532	0.527	0.521	0.519	0.510	0.352	0.329
1915-1	S3	G	1	0.509	0.507	0.506	0.504	0.502	0.412	0.374
1915-2	S3	G	1	0.546	0.540	0.536	0.532	0.526	0.396	0.374
1920-1	S3	G	2	0.581	0.572	0.565	0.559	0.554	0.399	0.390
1920-2	S3	G	2	0.538	0.533	0.531	0.527	0.523	0.400	0.373
1930-2	S3	G	3	0.525	0.519	0.514	0.510	0.506	0.362	0.314
1915-1	S3	UG	1	0.575	0.572	0.566	0.565	0.562	0.423	0.409
1915-2	S3	UG	1	0.515	0.513	0.512	0.510	0.508	0.430	0.410
1920-1	S3	UG	2	0.550	0.545	0.438	0.535	0.531	0.405	0.384
1920-2	S3	UG	2	0.543	0.535	0.531	0.522	0.518	0.384	0.369
1930-1	S3	UG	3	0.511	0.507	0.505	0.502	0.497	0.394	0.371
1930-2	S3	UG	3	0.554	0.550	0.543	0.541	0.537	0.394	0.356
1919-1	S4	G	1	0.589	0.586	0.582	0.578	0.576	0.470	0.464
1919-2	S4	G	1	0.574	0.567	0.562	0.557	0.554	0.381	0.369
1927-1	S4	G	2	0.547	0.535	0.529	0.524	0.516	0.313	0.299
1927-2	S4	G	2	0.481	0.473	0.471	0.468	0.465	0.343	0.277
1929-1	S4	G	3	0.610	0.598	0.592	0.582	0.576	0.427	0.404
1929-2	S4	G	3	0.615	0.609	0.606	0.601	0.599	0.454	0.426
1919-1	S4	UG	1	0.563	0.560	0.557	0.554	0.551	0.444	0.435
1919-2	S4	UG	1	0.520	0.517	0.515	0.512	0.511	0.416	0.399
1927-1	S4	UG	2	0.513	0.510	0.506	0.504	0.499	0.344	0.307

A1.13 Cont'd

Plot ID	TRT	GRZ	REP	0	0.4	1	2.5	5	10	30
				(-kPa)						
1927-2	S4	G	2	0.481	0.473	0.471	0.468	0.465	0.343	0.277
1929-1	S4	G	3	0.610	0.598	0.592	0.582	0.576	0.427	0.404
1929-2	S4	G	3	0.615	0.609	0.606	0.601	0.599	0.454	0.426
1919-1	S4	UG	1	0.563	0.560	0.557	0.554	0.551	0.444	0.435
1919-2	S4	UG	1	0.520	0.517	0.515	0.512	0.511	0.416	0.399
1927-1	S4	UG	2	0.513	0.510	0.506	0.504	0.499	0.344	0.307
1927-2	S4	UG	2	0.516	0.514	0.513	0.510	0.508	0.317	0.277
1929-1	S4	UG	3	0.605	0.598	0.594	0.588	0.582	0.444	0.421
1914-1	S5	G	1	0.555	0.549	0.546	0.545	0.540	0.417	0.408
1914-2	S5	G	1	0.656	0.650	0.648	0.642	0.640	0.473	0.449
1923-1	S5	G	2	0.577	0.567	0.555	0.547	0.538	0.329	0.309
1925-1	S5	G	3	0.446	0.442	0.439	0.434	0.432	0.302	0.263
1925-2	S5	G	3	0.520	0.510	0.504	0.501	0.493	0.333	0.288
1914-1	S5	UG	1	0.602	0.593	0.584	0.582	0.574	0.427	0.400
1914-2	S5	UG	1	0.699	0.685	0.678	0.670	0.662	0.523	0.483
1923-1	S5	UG	2	0.541	0.528	0.523	0.520	0.514	0.375	0.330
1925-1	S5	UG	3	0.476	0.472	0.468	0.464	0.462	0.306	0.280
1925-2	S5	UG	3	0.517	0.512	0.508	0.504	0.499	0.328	0.299

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5). G: Grazed; UG: Un-grazed.

A1.14 Soil beta-glucosidase enzymes (μg g^{-1} h^{-1}), urease enzymes (μg g^{-1} h^{-1}), and microbial biomass carbon (mg kg^{-1}) for 0-5 cm depth in 2017. TRT, treatment; GRZ, grazing; REP, replication; MBC, microbial biomass carbon.

Plot ID	TRT	GRZ	REP	Urease	Beta-glucosidase	MBC	MBN
1916	CNT	UG	1	156.9	99.0	293.6	-
1922	CNT	UG	2	163.5	112.5	277.2	-
1928	CNT	UG	3	164.2	104.5	276.2	6.9
1917	S1	UG	1	312.8	277.3	1029.7	57.9
1921	S1	UG	2	141.9	132.6	308.0	1.5
1924	S1	UG	3	249.0	91.2	219.1	13.7
1913	S2	UG	2	257.2	131.4	448.7	14.4
1918	S2	UG	1	311.7	313.0	636.0	26.4
1926	S2	UG	3	195.6	154.9	437.0	10.1
1915	S3	G	1	212.9	142.4	-	46.8
1920	S3	G	2	249.9	252.8	378.5	1.5
1930	S3	G	3	330.4	221.1	292.3	22.6
1915	S3	UG	1	235.5	411.7	497.6	13.8
1920	S3	UG	2	232.2	176.4	532.6	13.9
1930	S3	UG	3	-	159.6	457.8	52.7
1919	S4	G	1	180.5	228.6	508.0	17.5
1927	S4	G	2	109.5	-	158.6	-
1929	S4	G	3	513.0	592.7	714.1	36.6
1919	S4	UG	1	167.5	221.1	-	-
1927	S4	UG	2	228.6	333.6	406.3	5.4
1929	S4	UG	3	410.4	320.7	429.3	21.7
1914	S5	G	1	247.7	335.9	690.2	32.1
1923	S5	G	2	129.0	111.4	457.7	8.6
1925	S5	G	3	133.0	174.4	209.2	1.8
1914	S5	UG	1	190.6	256.1	-	-
1923	S5	UG	2	376.3	351.7	604.0	18.8
1925	S5	UG	3	93.5	84.1	182.8	8.4

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5). G: Grazed; UG: Un-grazed.

A1.15 Soil carbon fraction (μg g^{-1}) for 0-5 and 5-15 cm depths in 2017. TRT, treatment; GRZ, grazing; REP, replication.

Plot ID	TRT	GRZ	REP	Depth (cm)	Labile C	Stable C	Inert C (1M)	Inert C (6M)
1916	1	UG	1	0-5	38.0	83.4	424.6	235.8
1916	1	UG	1	5-15	24.3	43.9	102.4	145.6
1922	1	UG	2	0-5	33.6	94.9	479.3	178.8
1922	1	UG	2	5-15	19.9	39.2	271.0	116.9
1928	1	UG	3	0-5	15.4	31.3	226.9	230.8
1928	1	UG	3	5-15	13.9	21.6	191.9	158.4
1917	2	UG	1	0-5	29.5	80.1	267.3	172.1
1917	2	UG	1	5-15	21.0	41.8	110.3	121.7
1921	2	UG	2	0-5	33.5	89.9	157.9	190.2
1921	2	UG	2	5-15	21.6	41.3	227.6	123.5
1924	2	UG	3	0-5	20.9	37.2	147.5	153.7
1924	2	UG	3	5-15	15.3	20.3	111.8	107.7
1913	3	UG	2	0-5	30.6	69.0	251.8	183.2
1913	3	UG	2	5-15	16.3	32.9	116.6	145.8
1918	3	UG	1	0-5	31.2	66.5	204.6	175.2
1918	3	UG	1	5-15	22.1	42.4	108.3	97.0
1926	3	UG	3	0-5	38.2	73.4	255.8	196.3
1926	3	UG	3	5-15	20.0	35.3	241.6	137.6
1915	4	G	1	0-5	28.9	76.4	142.9	230.8
1915	4	G	1	5-15	20.9	39.8	102.7	174.4
1920	4	G	2	0-5	37.6	77.4	138.1	186.1
1920	4	G	2	5-15	22.3	42.1	128.0	115.7
1930	4	G	3	0-5	25.5	93.8	337.1	342.9
1930	4	G	3	5-15	22.1	44.8	246.8	244.1
1915	4	UG	1	0-5	30.1	67.5	203.7	246.1
1915	4	UG	1	5-15	18.2	35.9	94.6	150.2
1920	4	UG	2	0-5	35.7	105.2	241.3	183.4
1920	4	UG	2	5-15	30.2	55.3	103.8	130.6
1930	4	UG	3	0-5	22.8	86.0	418.2	281.3
1930	4	UG	3	5-15	22.3	45.9	303.6	177.9
1919	5	G	1	0-5	28.9	81.8	146.8	155.3
1919	5	G	1	5-15	22.1	48.8	94.0	128.0
1927	5	G	2	0-5	22.5	57.5	284.0	158.7
1927	5	G	2	5-15	15.7	26.5	207.6	129.3
1929	5	G	3	0-5	30.4	83.2	240.6	238.4
1929	5	G	3	5-15	20.8	49.0	169.6	162.2

A1.15 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	Labile C	Stable C	Inert C (1M)	Inert C (6M)
1919	5	UG	1	0-5	32.6	122.1	245.4	292.4
1919	5	UG	1	5-15	18.6	43.1	95.4	124.7
1927	5	UG	2	0-5	21.7	61.2	358.2	275.3
1927	5	UG	2	5-15	16.8	26.0	167.8	172.3
1929	5	UG	3	0-5	35.0	89.7	217.4	205.3
1929	5	UG	3	5-15	24.7	43.9	121.5	150.5
1914	6	G	1	0-5	29.3	68.0	219.9	242.3
1914	6	G	1	5-15	20.4	41.1	132.0	174.6
1923	6	G	2	0-5	31.2	77.6	279.6	215.4
1923	6	G	2	5-15	20.2	40.3	243.6	147.7
1925	6	G	3	0-5	22.0	43.9	259.7	219.4
1925	6	G	3	5-15	14.1	20.2	168.6	130.2
1914	6	UG	1	0-5	36.1	82.5	203.4	208.5
1914	6	UG	1	5-15	20.3	39.9	102.6	147.6
1923	6	UG	2	0-5	31.4	89.1	514.9	185.1
1923	6	UG	2	5-15	19.0	34.8	191.8	172.1
1925	6	UG	3	0-5	21.4	43.2	340.9	215.5
1925	6	UG	3	5-15	18.5	26.0	287.1	142.7

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5). G: Grazed; UG: Un-grazed.

A1.16 Soil nitrogen fraction (μg g^{-1}) for 0-5 and 5-15 cm depths in 2017. TRT, treatment; GRZ, grazing; REP, replication.

Plot ID	TRT	GRZ	REP	Depth (cm)	Labile N	Stable N	Inert N (1M)	Inert N (6M)
1916	1	UG	1	0-5	2.62	3.35	33.4	28.8
1916	1	UG	1	5-15	1.41	1.74	8.4	15.1
1922	1	UG	2	0-5	1.15	4.35	33.1	29.5
1922	1	UG	2	5-15	0.69	1.74	18.4	19.6
1928	1	UG	3	0-5	0.76	0.95	17.4	19.6
1928	1	UG	3	5-15	0.75	0.54	17.5	15.3
1917	2	UG	1	0-5	2.50	3.47	21.9	21.1
1917	2	UG	1	5-15	1.21	1.77	8.9	13.9
1921	2	UG	2	0-5	1.22	4.51	12.3	20.4
1921	2	UG	2	5-15	0.71	2.02	20.1	18.5
1924	2	UG	3	0-5	0.82	1.25	13.3	15.8
1924	2	UG	3	5-15	0.36	0.56	9.3	13.3
1913	3	UG	2	0-5	2.07	2.64	8.9	13.4
1913	3	UG	2	5-15	1.24	1.36	9.6	10.2
1918	3	UG	1	0-5	1.55	2.75	15.3	21.5
1918	3	UG	1	5-15	1.04	1.84	9.0	11.4
1926	3	UG	3	0-5	1.48	2.23	16.7	25.1
1926	3	UG	3	5-15	0.77	1.06	19.5	19.1
1915	4	G	1	0-5	4.91	3.37	13.5	14.3
1915	4	G	1	5-15	1.49	1.67	9.3	10.5
1920	4	G	2	0-5	1.30	3.60	10.0	19.2
1920	4	G	2	5-15	0.76	2.07	10.1	13.8
1930	4	G	3	0-5	1.41	4.01	32.4	20.7
1930	4	G	3	5-15	0.86	1.66	24.9	17.3
1915	4	UG	1	0-5	2.36	2.83	16.9	14.6
1915	4	UG	1	5-15	1.10	1.54	7.9	9.5
1920	4	UG	2	0-5	1.79	5.30	26.7	28.0
1920	4	UG	2	5-15	1.22	2.70	7.5	14.4
1930	4	UG	3	0-5	1.38	3.90	41.0	21.2
1930	4	UG	3	5-15	0.81	1.78	30.0	16.0
1919	5	G	1	0-5	1.46	3.74	10.9	18.0
1919	5	G	1	5-15	0.90	2.16	6.8	13.3
1927	5	G	2	0-5	1.38	1.85	18.6	17.7
1927	5	G	2	5-15	0.85	0.84	13.7	15.7
1929	5	G	3	0-5	1.60	2.91	27.2	17.0
1929	5	G	3	5-15	1.06	1.58	18.8	15.2
1919	5	UG	1	0-5	2.13	5.30	18.1	31.0

A1.16 Cont'd

Plot ID	TRT	GRZ	REP	Depth (cm)	Labile N	Stable N	Inert N (1M)	Inert N (6M)
1919	5	UG	1	5-15	0.97	1.98	7.1	13.9
1927	5	UG	2	0-5	1.24	1.84	23.8	23.6
1927	5	UG	2	5-15	0.92	0.89	12.5	18.1
1929	5	UG	3	0-5	2.06	3.20	24.3	16.3
1929	5	UG	3	5-15	1.17	1.33	14.0	14.2
1914	6	G	1	0-5	2.80	2.76	18.1	15.9
1914	6	G	1	5-15	1.36	1.68	10.9	9.2
1923	6	G	2	0-5	1.14	3.71	20.4	28.3
1923	6	G	2	5-15	0.75	1.77	18.1	18.1
1925	6	G	3	0-5	1.79	2.13	18.7	28.8
1925	6	G	3	5-15	0.88	0.84	12.4	18.3
1914	6	UG	1	0-5	3.17	3.27	17.7	13.6
1914	6	UG	1	5-15	1.33	1.51	8.1	10.2
1923	6	UG	2	0-5	1.32	4.64	33.7	31.4
1923	6	UG	2	5-15	0.72	1.64	11.9	24.8
1925	6	UG	3	0-5	1.06	1.98	27.3	21.3
1925	6	UG	3	5-15	0.70	1.00	20.8	21.3

CNT, Continuous spring wheat (control); S1, Sunflower (Helianthus annuus L.)-Spring wheat (Triticum aestivum L.)-Cover Crop-Corn (Zea mays L.)-Pea (Pisum sativum L.)/Barely (Hordeum vulgare L.) (sequence 1); S2, Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower (sequence 2); S3, Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat (sequence 3); S4, Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop (sequence 4); S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn (sequence 5). G: Grazed; UG: Un-grazed.

Table 5.1. Means of soil bulk density (BD) and soil organic carbon (SOC) as influenced by different cropping sequences for the 0-60 cm depth in 2016.

Treatments	BD (Mg m^{-3})	SOC (g Kg^{-1})
Rotation (R) [§]		
1	1.32[a†]	16.4[b]
2	1.34[a]	20.7[b]
3	1.32[a]	11.9[b]
4	1.19[b]	23.1[a]
5	1.29[ab]	19.4[b]
6	1.25[ab]	14.7[b]
	Analysis of variance *P*>*F*	
R	0.01	0.007
Depth (D)	0.004	<0.001
R×D	0.81	0.956

[§]CNT: Continuous spring wheat (control). S1: Sunflower (*Helianthus annuus* L.)-Spring wheat (*Triticum aestivum* L.)-Cover Crop-Corn (*Zea mays* L.)-Pea (*Pisum sativum* L.)/Barely (Hordeum vulgare L.). S2: Spring wheat- Cover Crop-Corn-Pea/Barely-Sunflower. S3: Cover Crop-Corn-Pea/Barely-Sunflower-Spring wheat. S4: Corn-Pea/Barely-Sunflower-Spring wheat-Cover Crop. S5: Pea/Barely-Sunflower-Spring wheat-Cover Crop-Corn.

[†]Means within the same column followed by different small letters are significantly different at $P<0.10$ for the treatments.

APPENDIX 2

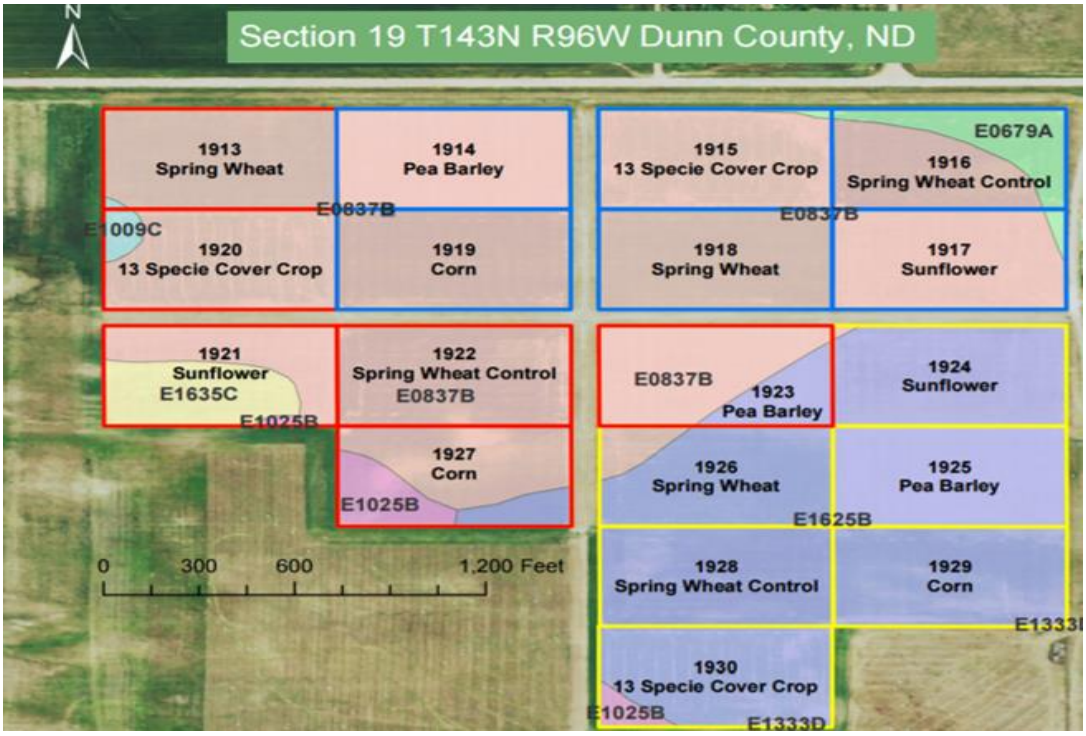
Statistical analysis code used for analysis of soil quality parameters

```
proc import datafile='C:\Users\Hanxiao.Feng\Desktop\SOC\SOC.csv'
out=dt;run;


/** check and clean the data **/
proc means data=dt n mean std max min;
var SOC;
run;


data dt1; set dt;
if SOC<0 or SOC=0 or SOC="." then delete;run;


proc means data=dt1 n mean std max min;
var SOC;
run;


proc capability data=dt1 no print; /**test normal distribution of change variable* method: histogram*/
histogram SOC/normal;
run;


/** summary: mean sd by dep by rot**/
proc sort data=dt1 out=dt2;
by dep rot; run;
```

```
ods output summary=summ_m;
proc means data=dt2 n mean std;
by dep rot;
var SOC;
run;
ods output close;
proc export data=summ_m
  outfile="C:\Users\Hanxiao.Feng\Desktop\SOC\dep-rot-mean.csv"
  dbms=csv
  replace;
run;


/* Mixed model for rot, grz, depth to get fixed effects (p-values) and results of
comprisions for all depths*/


proc glimmix data=dt1 plots=residualpanel;  /*plots command is to draw plots for
dignosing the mixed model*/
class rot grz dep rep;
model SOC = rot grz dep rot*grz rot*dep grz*dep rot*grz*dep/alpha=0.1;
random rep rep*rot rep*rot*dep;
lsmeans rot grz dep/ bylevel lines alpha=0.1 adjust=tukey ;
run;


/* using mixed model in dep 1*/
data d1;set dt1;
where dep=1;
run;
```

```
proc glimmix data=d1 plots=residualpanel;  /*plots command is to draw plots for
dignosing the mixed model*/

class rot grz rep;

model SOC = rot grz  rot*grz/alpha=0.1;

random rep;

lsmeans rot grz rot*grz/ bylevel lines alpha=0.1  ;

run;
```

APPENDIX 3



The layout of the study site at Dunn County, Dickinson, ND

Livestock grazing in the field

Saturation of the soil core samples (left) and the analysis of soil water retention (right)

Oven dried soil stable aggregates (left) and unstable aggregates (right)


Grinding of soil samples for the analysis of soil organic carbon and total nitrogen


Incubation of soil samples and analysis for beta-glucosidase enzymes activity

Acid extraction of soil samples for the analysis of carbon and nitrogen fractions

VITA

Hanxiao Feng was born in Anyang, Henan Province, China. She received her bachelor degree from College of Science Department majoring in Applied Chemistry in 2015 from Henan Agricultural University, Henan, China. She joined in Agronomy, Horticulture, and Plant Science Department to pursue her MS degree in Plant Science at South Dakota State University as a graduate student in Spring 2016 under supervision of Dr. Sandeep Kumar.